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ELECTROLYTIC CORROSION OF IRON IN SOILS

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I. INTRODUCTION

The term "electrolytic corrosion" is most frequently used to indicate corrosion caused by the discharge of an electric current which enters the metal from external sources. During recent years, however, the theory has been widely accepted that all corrosion in water solutions is essentially electrolytic in its nature, and in consequence there have come into use a variety of terms such as "galvanic action," "stray current electrolysis," "self-corrosion," etc., to distinguish between the cases of corrosion originating from different causes. Thus, corrosion of buried iron may be due to galvanic action caused by physical or chemical differences between adjacent points on the surface of the metal, to the presence of foreign substances in the soil, such as coke cinders, iron oxides, etc., which set up local galvanic action, or it may be due to the discharge of electric currents that have entered the structure at some remote point. In the present paper the terms "electrolysis" and "electrolytic corrosion" are used to designate corrosion caused by the discharge of electric current which has entered the metal from some outside source, while all other forms of corrosion in which the electric currents originate within the corroding system itself from whatever cause are referred to as "self-corrosion." It should be pointed out at the outset, however, that these two general classes of corrosion are by no means independent of each other, since the presence of either kind of corrosion generally affects in marked degree the nature and extent of the other under a given set of conditions. This mutual influence is such as to be of considerable practical importance, and in particular it often greatly increases the difficulty of obtaining trustworthy experimental data in regard to electrolytic corrosion proper.

The data herein presented represent a portion of the work done by the Bureau of Standards in connection with a more general investigation of the subject of electrolysis and electrolysis mitigation, which has been in progress for some time past. The present paper is designed to deal only with the fundamental laws governing electrolytic corrosion under practical conditions, and relates to self-corrosion only in so far as it is necessary to distinguish between the two classes. The subject of the prevention of electrolytic damage is referred to only incidentally, when occasion requires, in order to interpret the significance of results obtained. This matter of electrolysis prevention has been given much attention and will be treated at some length in a report which will be issued shortly by the Bureau of Standards, dealing exclusively with the subject of electrolysis mitigation.

In studying the phenomena of electrolytic corrosion in soils under practical conditions many variables are encountered which tend in greater or less degree to affect the results. Among these may be mentioned the current density at the surface of the metal, the moisture content of the soil, the presence of oxygen either in the gaseous state or dissolved in soil waters. The latter not only affects the rate of corrosion but also affects the character of the end products of the reactions, and thus to some extent has a bearing on the question of diagnosing the cause of particular cases of corrosion. The temperature of the soil is also important, particularly because of its effect on the current flow. In the case of iron, the formation of oxids as a result of the initial corrosion may complicate matters because of their possible action in stimulating galvanic action. Other factors, such as the mechanical and chemical properties of the soil, the depth of burial of the metal, the limitation of current flow due to polarization, the formation of high resistance films on the surface of the metal, and the pitting of the surface, due to a variety of causes, may likewise act to increase or decrease the rate at which damage may progress, and therefore require special investigation. Finally, since it is not practicable to carry on all experiments in the field under practical conditions, it is necessary to study the possible differences in results that may in some cases occur between experiments performed in the laboratory and in the field. It is these factors that are dealt with in the following pages, and while the investigations have in most cases not yet been completed, we believe that the data thus far obtained will be of sufficient interest to justify a report of progress at this time.

While the corrosion of iron by electric currents may be influenced by a variety of causes, the data to be presented later show that under most practical conditions the extent of the corrosion is to a large extent a function of the quantity of electricity that is discharged from a given surface. This is a quantity that can be readily measured under laboratory conditions and we have therefore determined, in all cases, the corrosion as a function of the ampere-hour discharge from the anode. The results are expressed in terms of the "corrosion efficiency." If the corrosion of the anode is the sole reaction involved at the anode, then, according to Faraday's law, 96 540 coulombs are required to corrode 1 gram equivalent of the metal and the corrosion efficiency is said to be 100 per cent. In most cases, however, the actual corrosion noted is either greater or less than this amount, and the percentage which the actual corrosion in any case is of the theoretical amount may be called the "efficiency of electrolytic corrosion," or more briefly, "corrosion efficiency," under those conditions. The experimental data presented in the first part of this paper show how the efficiency of corrosion is affected by the varying physical conditions encountered in practice.

The corrosion efficiencies are in all cases calculated on the assumption that the iron is divalent. The experiments presented show that in most cases at least this was true, since, as a rule, the corrosion efficiencies observed have been near or above 100 per cent. This is therefore the logical basis on which to figure the efficiency of corrosion. In those cases where the corrosion efficiency was very low it may be due in part to the iron taking the ferric state, and such tendency, when it exists, may therefore be regarded as one of a number of possible causes of low efficiency of corrosion. The various factors enumerated above which affect the efficiency of corrosion of iron in soils are discussed in detail in a later part of this paper.

1. ARRANGEMENT OF APPARATUS

The methods of conducting the experiments recorded below were, in general, the same, and may therefore be described once for all.

The local earths used in the laboratory tests were from virgin soil near the laboratory, sifted to remove stones and to insure uniformity. This earth was mixed with the desired amount of distilled water and placed in tin cans, which served as cathodes. The bottoms of the cans were separated from the earth by a thick layer of paraffin or other insulating material, so that the discharge from the anode placed in the center of the can would be substantially uniform and only toward the sides of the can. The outside of the cans were insulated from each other by several layers of heavy paraffined paper. In a number of experiments, however, the test specimens were buried in virgin soil out of doors in order to compare directly the corrosion found under these conditions with the corrosion which resulted when the tests were made in the laboratory.

2. CLEANING OF ANODES

In cleaning the anodes and determining their losses, a number of precautions are necessary. It has been shown that many solutions render iron at least temporarily passive. Such solutions are, of course, not desirable for cleaning iron previous to a test. The iron used was filed and sandpapered to remove dirt and scale, cut into suitable lengths, stamped on one end with steel numbers for identification, and weighed. Rubber-covered leads were then soldered to the unnumbered ends of the anodes and both ends covered with paraffin or pitch. To make these stick to the iron it is necessary that it should be rather hot when they are applied. The specimens were then thoroughly washed with gasoline to remove any grease due to handling and finally dried with a towel. At the close of the experiment the specimens were washed and brushed to remove all loose dirt and then made cathode in a 2 per cent solution of sulphuric acid with a high-current density. To prevent plating a noncorrodable anode should be used. This method of cleaning was developed after various mechanical and chemical methods had been tried with inconsistent results and has proven very satisfactory. The specimens came from the solution perfectly clean within 10 to 30 minutes and careful tests have shown that clean iron subjected to the treatment suffers no loss. The method seems very much preferable to any mechanical method we have tried, since when the rust sticks very tightly or the iron is rough it is impossible to remove the corrosion products without scraping off some of the iron with them. In a few instances where it was not convenient to clean the iron electrolytically, as in the case of hollow anodes too small to permit the interior to be protected by inserting an anode, a solution of ammonium citrate has been used. This latter method is satisfactory, except in the case of deep pits, especially if a warm solution is used.

The paraffine protecting the ends of the specimens was removed by gasoline and the pitch by toluol. The solder attacking the leads was melted and carefully wiped off. We have also tried dissolving the solder by mercury, but the process is slow unless heat is used, and the result no better than the easier method.

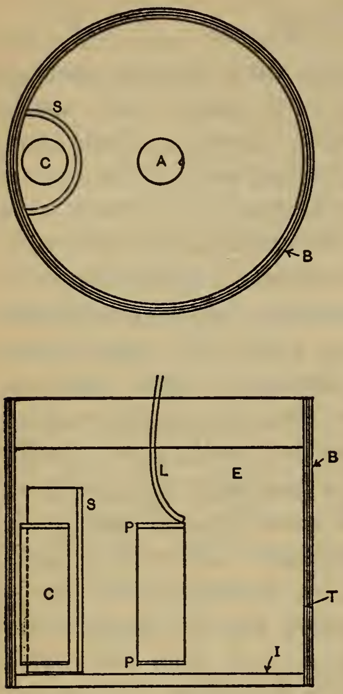

Fig. 1.—*Showing arrangement of apparatus for corrosion tests*

A, anode; B, containing vessel; T, tar coating; I, insulating bottom; P, paraffin coating on ends of anodes; L, lead; C, check specimen; S, insulating shield

3. CHECK SPECIMENS

Correction for the loss by the anodes due to self-corrosion was made by placing a check specimen inside each can and screening it from the anode by a shield of glass or paraffined paper. Fig. 1 shows the arrangement of the anode and check specimen. The loss of this check specimen has been deducted from the loss of the anode and the difference used as the loss due to electrolysis. It will be shown later that the loss of check specimen in a can with an anode is considerably greater than that of a similar check specimen in a separate vessel of the same earth and it seems therefore that part of the loss in the former case is due to some effect of the current and should be charged against it. The corrosion efficiencies found are consequently lower than if check specimens in separate cans were used. However there are several advantages in keeping the check specimen in the can with the anode and the increased loss on this account is usually small compared with the total loss of the anode.

4. DETERMINATION OF AMPERE HOURS

To obtain the corrosion efficiency it is of course necessary not only to determine accurately the loss of the anode, but equally essential to know the quantity of electricity discharged by it. To obtain this the specimens were so arranged that the current could be read at frequent intervals, compensation being provided where necessary for the resistance of the milliammeter. Curves were plotted showing the relation between the current and time, and the area between the curve and the axes determined with a planimeter. While the exact current values between times of observation are unknown, the areas represent a value of the ampere hours sufficiently accurate for practical purposes, and the large number of circuits operating at one time made the use of more accurate recording instruments out of the question.

II. FACTORS AFFECTING EFFICIENCY OF CORROSION

1. EFFECT OF CURRENT DENSITY

A number of investigators have reported experiments showing that the amount of corrosion which results from a given ampere hour discharge varies greatly from the theoretical amount. Among these may be mentioned the work of Hayden,[1] and of W. W. Haldane Gee,[2] who worked with high current densities, and observed that there was a marked tendency for the iron to become passive, the resulting corrosion being considerably less than the theoretical amount. In general this tendency toward passivity was much more marked when the current density was very high. These experiments were carried out with test specimens immersed in liquid baths, however, so that the conditions were very different from those which prevail in ordinary street soils. Ganz[3] has reported the results of experiments carried out in certain soils, which showed that the actual corrosion observed was much greater than the theoretical amount, in some cases the loss in weight being as much as several times the loss calculated from Faraday's law. In these experiments very low current densities were used and the earth contained considerable quantities of salt, and this may have affected the result. The authors have carried out several series of experiments in which the aim has been to maintain conditions as nearly as possible approximating those which will be encountered in practice, both as regards soil conditions and cur-

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[1] Jour. Franklin Inst., Vol. 172, p. 295.

[2] Jour. Municipal School of Tech., Manchester, Vol. 2, 1910.

[3] Proc. A. I. E. E., June, 1912, pp. 1001–1010.

rent densities. The soil used was a virgin soil taken from a sparsely settled portion of the residential district of Washington. An analysis was made of a typical sample of the soil for those ingredients which are most likely to affect corrosion, the results being shown at the top of Table 1 along with the data on efficiency of corrosion.

In determining the current densities to be used values were chosen of such magnitude as could give rise to considerable injury within a period varying from a few months to 15 or 20 years. For example, the highest value used was about 5 milliamperes per square centimeter, which under uniform distribution and at 100 per cent efficiency of corrosion would cause the corrosion to progress inward at the rate of about 5.7 centimeters per year, which corresponds to a rate rarely exceeded under practical conditions. The minimum current density used was 0.05 milliamperes per square centimeter, which corresponds to a normal rate of corrosion of about 1 centimeter in 17 years. These extreme ranges represent therefore the limits between which the corrosion is of much practical importance.

Several series of experiments were made, the data presented in Tables 1 and 1a being typical of the series. The corrosion efficiencies under Table 1 are for a soil containing considerably less moisture than those under Table 1a, which are obtained on a soil practically saturated with water. In the former the test specimens were all imbedded in samples of earth placed in tin cans as described above, while in the second series half of the tests were run with specimens buried to a depth of about 2½ feet in the ground out of doors.

The data in Table 1 are plotted in Fig. 2, and those of Table 1 a are plotted in Figs. 3 and 4, the curve of Fig. 4 being a continuation of that of Fig. 3, but on a smaller scale. While the points do not lie on a smooth curve, because of a number of disturbing factors to be discussed later, the trend of the curves is nevertheless unmistakable. They show corrosion efficiencies varying greatly with the current density, the ranges being from about 20 to 140 per cent for the range of current density varying from about 5.0 to 0.05 milliamperes per square centimeter, the lower corrosion efficiencies being obtained at the higher current densities. All of the data in Tables 1 and 1 a are plotted as a single curve in Fig. 5, which, in spite of the irregularities in the individual points shows clearly the decided falling off in efficiency of corrosion with increase in current density. It is interesting to note here that the points in Fig. 5 marked with an x were taken out of doors in native earth while those marked with dots and circles were two separate series taken indoors, using small samples of earth in cans. The agreement between the different groups is

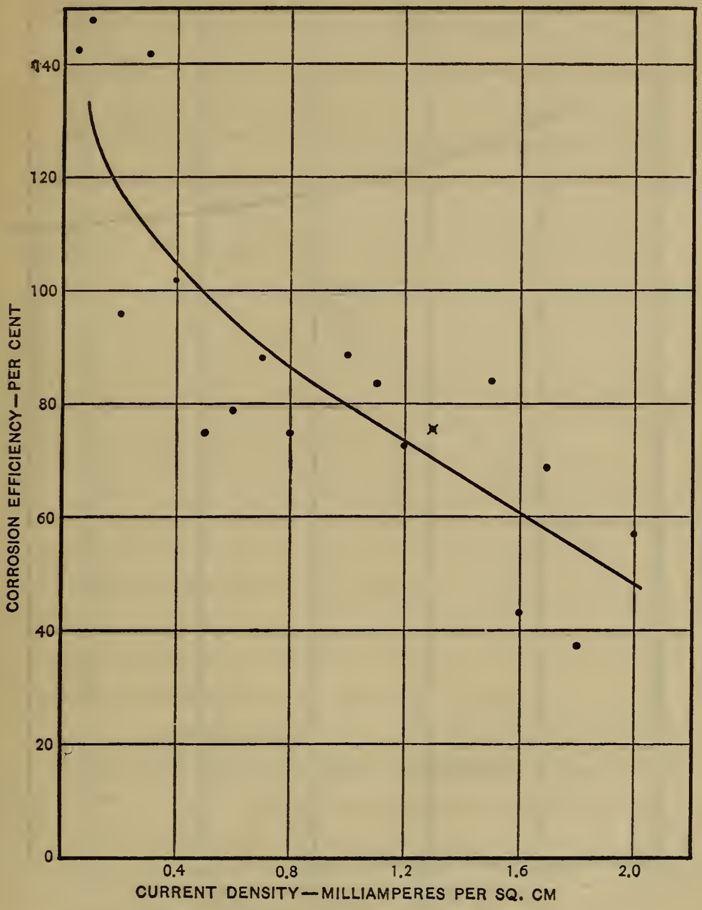

Fig. 2.—*Effect of Current Density on Efficiency of Corrosion*

fully as good as that between different points of the same group which indicates that the results obtained on small samples in the laboratory are substantially the same as those obtained on specimens buried in the earth out of doors. This gradual change in corrosion efficiency with current density does not appear in accord with the results of Hayden, Haldane Gee, and others, whose work with liquid electrolytes seemed to indicate an abrupt change in efficiency of corrosion from 100 per cent to zero at a critical current density.

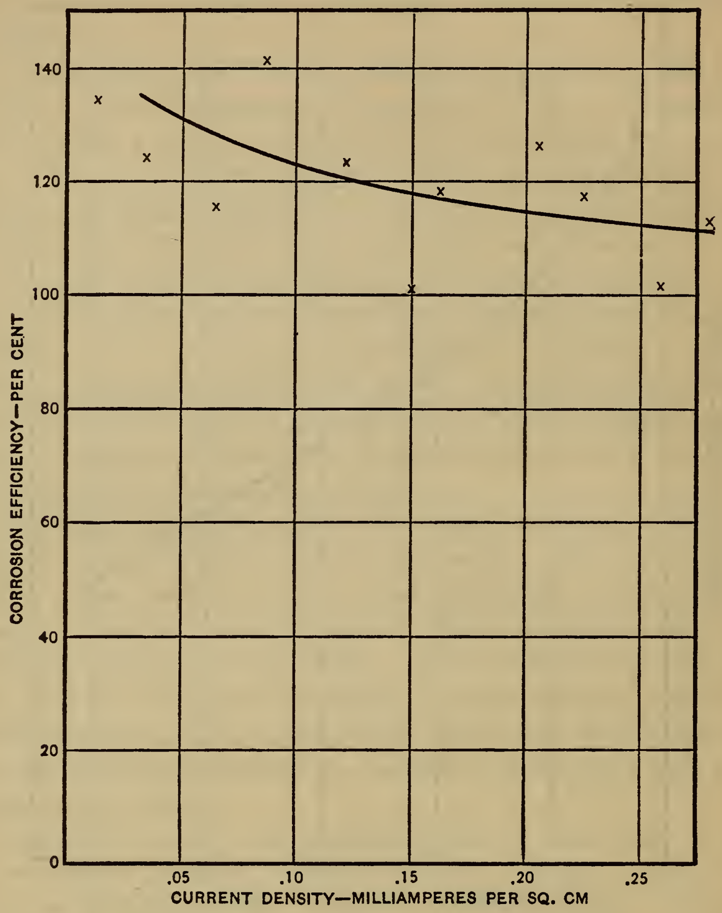

Fig. 3.—*Effect of Current Density on Efficiency of Corrosion*

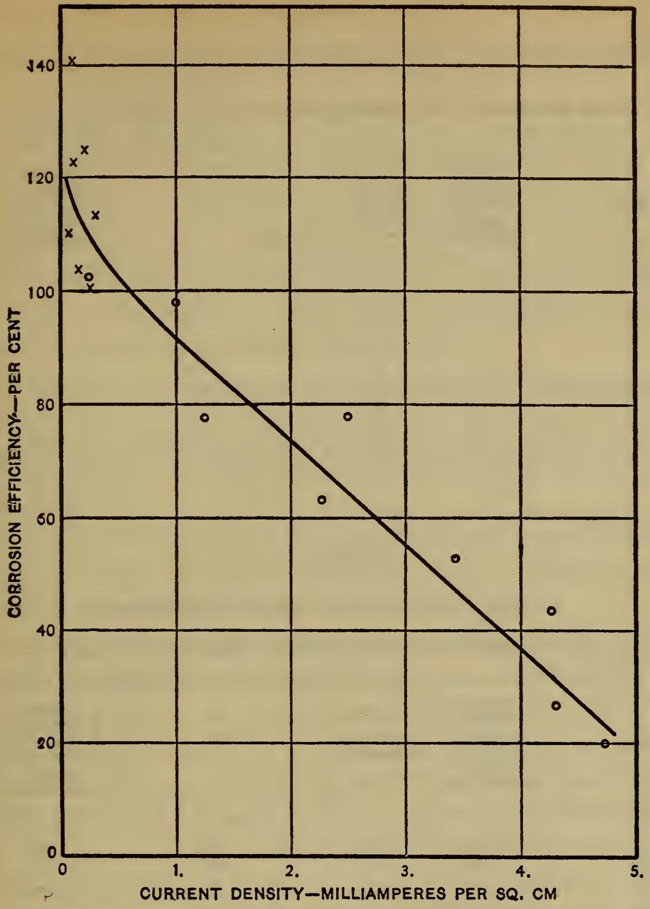

Fig. 4.—*Effect of Current Density on Efficiency of Corrosion*

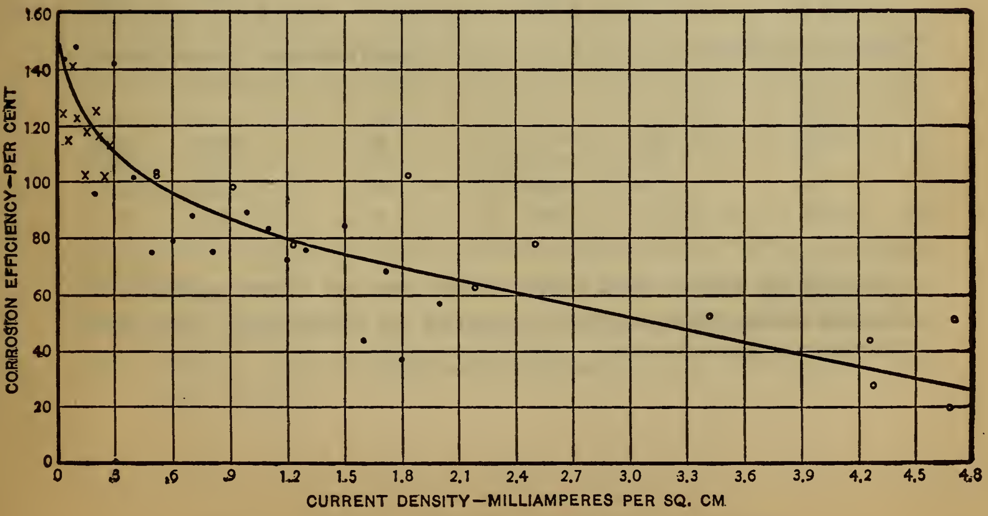

Fig. 5.—*Effect of Current Density on Efficiency of Corrosion*

TABLE 1

Relation between Current Density and Efficiency of Corrosion

[Partial analysis, per cent of moisture-free sample $\frac{\mathrm{Cl}}{0.002}$ $\frac{\mathrm{NO_3}}{0.002}$ $\frac{\mathrm{CO_3}}{0.003}$ $\frac{\mathrm{SO_4}}{0.004}$]

No.	Density, milliamperes per square centimeter	Efficiency of corrosion	No.	Density, milliamperes per square centimeter	Efficiency of corrosion
1	2.0	57.6	10	.8	75.0
2	1.8	37.4	11	.7	88.3
3	1.7	69.2	12	.6	79.1
4	1.6	43.2	13	.5	75.2
5	1.5	84.3	14	.4	102.1
6	1.3	75.8	15	.3	142.2
7	1.2	72.9	16	.2	96.2
8	1.1	83.8	17	.1	148.4
9	1.0	89.2	18	.05	142.9

TABLE 1 a

Current Density and Corrosion Efficiency

[Area of anodes 70.9 square centimeters. Time of run, 115 hours]

No.	Current density, milliamperes per square centimeter	Corrosion efficiency	No.	Current density, milliamperes per square centimeter	Corrosion efficiency
19	0.034	124.1	24	.163	118.3
20	.064	115.0	25	.206	125.8
21	.088	141.5	26	.222	117.1
22	.129	123.6	27	.258	101.8
23	150	104.6	28	.279	113.4

[72-hour run in saturated soil in laboratory 4-27-13 to 4-30-13. Exposed anode area 11.78 square centimeters]

29	0.48	102.5	34	2.50	78.1
30	1.01	98.1	35	3.45	52.9
31	1.26	78.3	36	4.27	43.6
32	1.84	102.2	37	4.29	27.4
33	2.28	63.6	38	4.72	20.4

It will be noted that these results do not show as high efficiencies of corrosion as those reported by Prof. Ganz,[4] who found

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[4] Proc. AI. E. E., June, 1912.

values ranging over 500 per cent. It should be noted, however, that the results obtained by Prof. Ganz were for the most part obtained on much lower current densities than were used in the present experiments. It is seen also from Fig. 5 that as the lower current densities are approached the curve tends rather strongly upward, indicating that if the current density had been reduced to the low value used by Ganz the corrosion efficiencies might have reached the high values found by him. As pointed out above, however, lower current densities than those used in the present series, although of great theoretical interest, are of little consequence from the practical standpoint.

2. EFFECT OF MOISTURE ON THE RATE OF CORROSION

The following experiments were tried to determine whether the amount of moisture in the soil affected the corrosion efficiency of iron buried in it.

A quantity of red clay soil was air dried and then distilled water was added, a can of earth taken out, more water added, etc., till six cans of earth had been obtained.

The ends of the specimens and the bottom and outside of the cans were insulated as in previous tests and small dishes of water placed inside the can to retard evaporation. The six cans were connected in series, the sides of the cans serving as cathodes and a current of 10 milliamperes giving about 1 milliampere per square centimeter was maintained by daily adjustments for 18 days. At the end of this time the resistance had increased so much that it was difficult to maintain the current and the specimens were therefore removed, cleaned, and weighed. The efficiency of corrosion was then computed, corrections being made for self-corrosion.

While the current was flowing, samples of the earth taken when the specimens were placed in the cans were dried for about a week in an oven at a temperature of 105° and the percentage of moisture computed from the loss of weight. The per cent of moisture is expressed in terms of the earth before drying.

The experiment was repeated, using 12 samples of earth. In order to run the entire set in series it was necessary to use a current of 2 milliamperes instead of 10 milliamperes as in the first trial. This may account for the difference in the results obtained in the two series. The methods were the same in each case. The results of these tests are given in Table 2 and those for the second series are plotted in Fig. 6.

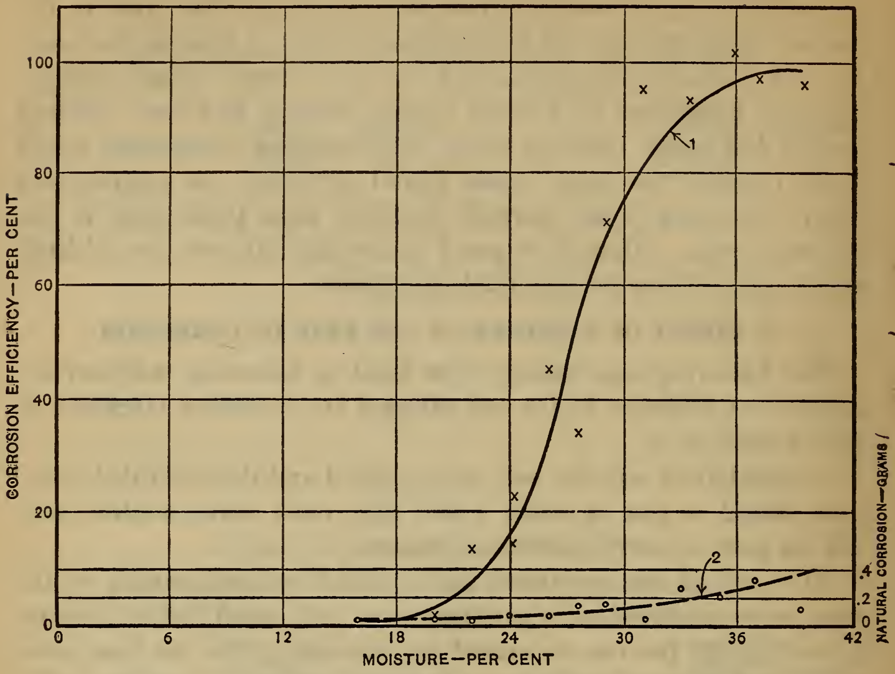

Fig. 6.—*Effect of Moisture Content of Soil on Efficiency of Corrosion*

TABLE 2

Effect of Moisture on Corrosion

No.	Per cent moisture	Loss in grams			Per cent efficiency of corrosion
		Total	Natural	Electrical	
1	15.9	0.090	0.044	0.046	1.1
2	20.0	.110	.040	.070	1.6
3	22.5	.623	.039	.584	13.7
4	23.8	.715	.080	.635	14.9
5	26.0	2.002	.073	1.929	45.3
6	27.6	1.579	.145	1.434	33.7
7	28.9	3.192	.160	3.032	71.2
8	31.1	4.182	.121	4.061	95.4
9	33.3	4.217	.265	3.952	92.8
10	35.7	4.545	.207	4.338	101.9
11	37.0	4.463	.335	4.132	97.0
12	39.4	4.218	.125	4.093	96.2

Looking at the curves of self and electrolytic corrosion, it will be seen that where a point on one curve is too high, the corresponding point on the other curve is too low. Since the electrolytic curve was obtained after natural losses had been deducted it is evident that some of the irregularities are due to incorrect values of the natural loss. However, the natural loss is so small that in most cases it could not account for the entire variation in the electrolytic curve. Since all wrought iron contains more or less slag, it is probable that the presence of minute slag particles explains, in part at least, the pitting and variations of results from expected values.

The results of these tests show that the corrosion efficiency varies greatly with the moisture content of the soil, being so small as to be practically negligible when the soil is fairly dry, but approaching values of the order of 100 per cent when the soil becomes saturated. In these tests there was very little corrosion when the moisture content was below 20 per cent. It should not be assumed, however, that the numerical values given here will hold for all soils, since there is considerable uncertainty as to the conditions which actually prevail.

In the first place, the percentage of moisture required to produce a wet condition of the soil varies greatly with different soils so that the percentage of moisture can not be taken as a measure of the condition of dryness. In the red-clay soil used in these tests the soil appeared to be barely moist at 15 or 20 per cent moisture, whereas in many cases we have since encountered numerous soils in which 10 per cent of moisture caused it to appear quite wet. There may also be variations due to differences in soil composition which affect the efficiency of corrosion. Further, while the average current density in these experiments was maintained practically constant it is not improbable that the actual current density varied considerably. When the soil was practically saturated with water the current density would probably be nearly uniform, but as the moisture content is reduced and some of the pores in the soil became voids, there would be a tendency for the current to discharge locally at the points of contact between earth and iron, and it appears possible that this might give rise to great variation in the actual current density of the discharge. It has already been seen that at high current densities the efficiencies of corrosion tend to become smaller, so that the variations in efficiency of corrosion here observed as due to changes in moisture content may after all be due in large part to changes in current density. However this may be, the important fact is that the amount of corrosion per ampere hour is likely to be quite low in the case of fairly dry soils, while as the percentage of moisture approaches that corresponding to saturation the corrosion efficiency approaches 100 per cent for the particular value of current density used in this series, namely, 1 milliampere per square centimeter.

3. EFFECTS OF TEMPERATURE

In order to study the effects of temperature on the efficiency of corrosion of iron in soil, three series of experiments were carried out. In the first of these the temperature of the cans containing the earth samples was maintained practically constant at between zero and 1° C by means of an ice bath; the second was run at between 24° and 27° C, which corresponds to about average summer temperature in soils; and the third group was maintained at between 35° and 40° C by means of an automatically regulated oven. Four specimens were used in each group, and the current density was maintained practically constant at about 0.84 milliamperes per square centimeter.

The tests were all run in the same kind of earth, which was kept practically saturated with moisture. The results of these tests are given in Table 3. An examination of the values of efficiency of corrosion will show that they are practically independent of the temperature. It appears, therefore, that it is safe to assume that throughout the range of temperatures that are likely to be encountered under practical conditions temperature variations have no marked effect on the corrosion efficiency of iron in soils. This does not mean, however, that temperature is not an important factor in electrolysis under practical conditions, for the reverse is true; but this grows out of the effect of temperature on the resistance of the soil rather than on the efficiency of corrosion. It is shown in a later part of this paper that the resistance of soils varies with temperature in a very remarkable manner even within the ranges of temperature that are likely to occur in soils under ordinary conditions, and that the effect of this change in resistance on the current flow is such as to make the actual amount of electrolysis which may be expected vary greatly with temperature. This matter is discussed later under the head of earth resistance.

TABLE 3

Effect of Temperature on Corrosion Efficiency

[Average current density, 0.84 milliamperes/cm^2]

No.	Temperature	Corrosion efficiency
1	35 to 40° C	98.2
2		103.4
3		97.0
4		98.4
	Average	99.2
5	24 to 27° C	98.2
6		97.6
7		97.9
8		97.6
	Average	97.8
9	0 to 1° C	93.8
10		95.7
11		99.1
	Average	96.2

4. EFFECT OF DEPTH OF BURIAL ON EFFICIENCY OF CORROSION

Inasmuch as the efficiency of corrosion is found to vary greatly under different conditions, it was deemed advisable to investigate whether the depth to which a pipe is buried below the surface would have any effect on the efficiency of corrosion. Accordingly a number of specimens were prepared and buried in earth to distances varying from a few inches to about 6 feet. A check specimen was provided in each case to permit correction for self-corrosion, and it was so shielded as to prevent the passage of any current through it. The anodes and check specimens alternated with each other in the order given in Table 4. In correcting for self-corrosion the mean of the losses on the check specimens on both sides of each anode was used. The specimens were buried in virgin red clay soil and were run at an average current density of about 0.056 milliamperes per square centimeter for about 1490 hours. The results of the tests are shown in Table 4 and plotted

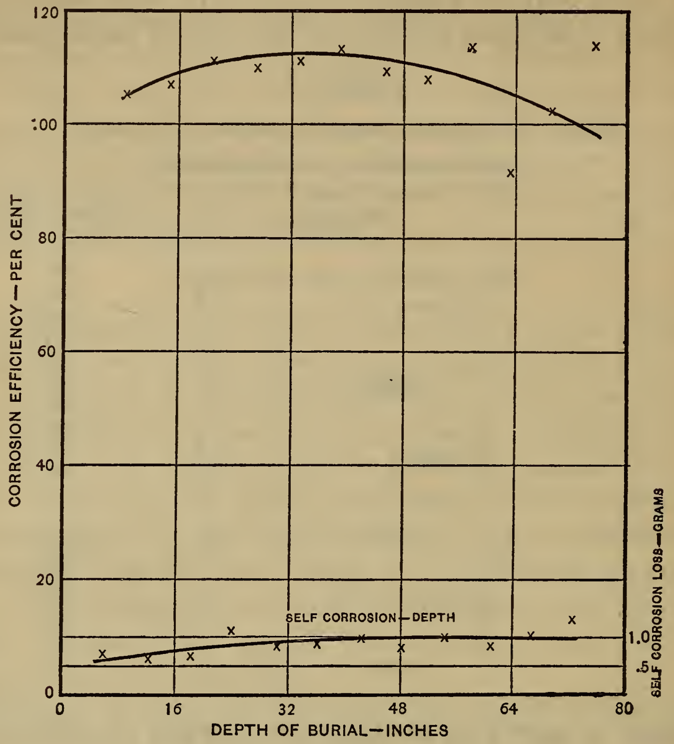

Fig. 7.—*Effect of Depth of Burial on Efficiency of Corrosion*

in Fig. 7, which gives curves of both self-corrosion and efficiency of corrosion as a function of depth.

TABLE 4

Effect of Depth of Burial on Natural and Electrolytic Corrosion

[Wrought-iron cylinders 2 inches long and 1¾ inches in diameter polished. Odd numbers carried current; even numbers are for natural corrosion. Area of surface, 70.9 square centimeters. Mean current density, about 0.056 milliamperes per square centimeter]

No.	Total loss	Electrical loss	Theoretical loss	Per cent efficiency of corrosion	Depth
	g	g	g		Inches
1	9.260	7.972	6.990	114	75
2	1.288				72
3	9.475	8.319	8.119	102	69
4	1.024				66
5	7.630	5.685	6.280	91	63
6	.875				60
7	10.862	9.929	8.785	113	57
8	.991				54
9	9.422	8.512	7.890	108	51
10	.829				48
11	8.505	7.593	6.959	109	45
12	.995				42
13	8.822	7.866	6.942	113	39
14	.916				36
15	8.225	7.341	6.618	111	33
16	.852				30
17	6.899	5.913	5.385	110	27
18	1.120				24
19	7.331	6.424	5.780	111	21
20	.694				18
21	4.667	3.993	3.732	107	15
22	.654				12
23	5.092	4.420	4.226	105	9
24	.690				6

It will be seen that the results, while somewhat irregular, indicate that there is but slight variation attributable to depth, although there seems to be a trend upward in the case of self-corrosion. The variation in efficiency of corrosion with depth is probably due to the fact that the moisture content varied with depth. The fact that no greater variation was observed is doubtless due to the fact that the tests were carried out at a time when the soil was fairly wet both near the surface and at greater depths. The results given above on the effect of moisture content indicate that if the experiments had been made in a fairly dry time, when there was considerable variation of moisture content with depth, the corrosion efficiency would probably have shown a corresponding variation. When conditions are such that there are considerable variations in moisture content with depth, as in a moderately dry time, for instance, the preceding data indicate that the efficiency of corrosion would probably also vary greatly with depth, being in general greater the greater the depth.

5. EFFECTS OF OXYGEN ON CORROSION OF IRON

Since, according to the electrolytic theory of corrosion, the presence of oxygen is an important factor in the production of self-corrosion of iron in the presence of water, it might be expected that the electrolytic corrosion of iron by stray currents would be affected in a marked degree by the content of dissolved oxygen in soil water. In order to investigate this point 10 anodes and a corresponding number of check specimens having an exposed area of 90 square centimeters each were prepared in the usual way, connected in series, and run on a practically constant current density of 0.056 milliampere per square centimeter. Five of these jars were so arranged that oxygen bubbled through the liquid continuously throughout the entire experiment, and the other five were immersed in the water without oxygen being passed through them. At the end of 183 hours the experiment was completed, the anodes were weighed, and the efficiencies of corrosion calculated. The data are given in Table 5, from which it will be seen that there is considerable variation in the efficiencies of corrosion for the individual specimens. These variations are so large that the difference between the average of the five specimens in the jars through which oxygen was passed (98.5 per cent) and the average for those specimens in the remaining jars (91 per cent) has but little significance. It is of course necessary to bear in mind in interpreting these results that even the water through which oxygen was not passed contained a good deal of oxygen in solution, so that any differences in efficiency of corrosion that might be indicated would be those due to a somewhat indefinite difference in the oxygen contained in the water.

TABLE 5

Effect of Oxygen on Efficiency of Corrosion

[Current density, 0.056 milliampere/cm^2; time, 183 hours; area of anodes, 90 cm^2]

A. OXYGEN ADDED

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
	g	g	g	Per cent
0	1.248	0.182	1.066	110.7
1	1.251	.312	.939	97.5
2	1.296	.330	.966	100.5
[5] 3	.993	.067	.929	96.5
4	1.128	.327	.801	87.0
	Average......	....	....	98.5

B. NO OXYGEN ADDED

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
[5] 5	0.886	0.030	0.873	90.6
6	.940	.027	.913	94.9
7	.913	.029	.884	91.7
8	.889	.030	.859	89.0
9	.895	.040	.855	88.7
	Average......	....	....	91.0

[5] Buried in sand.

TABLE 5a

Effect of Oxygen on Efficiency of Corrosion

[Theoretical loss, 0.730 gram; area of anodes, 15.2 square centimeters; current density, 1.45 milliamperes/cm^2]

WITHOUT OXYGEN

No.	Solution	Weights in grams		Loss	Corrosion efficiency
		Original	Final		
		g	g	g	Per cent
1	H_2O..............	51.326	50.624	0.702	96.2
2	H_2O..............	51.570	50.871	.699	95.8
3	10% Na_2SO_4.......	52.361	51.651	.710	97.3
4	10% Na_2SO_4.......	51.642	50.935	.707	96.9
	Average.....	....	....	....	96.5

TABLE 5a—Continued

WITH OXYGEN

No.	Solution	Weights in grams		Loss	Corrosion efficiency
		Original	Final		
		g	g	g	Per cent
5	H_2O	51.852	51.154	0.698	95.7
6	H_2O	52.725	52.044	.681	94.7
7	10% Na_2SO_4	51.467	50.759	.708	97.0
8	10% Na_2SO_4	51.034	50.317	.717	98.2
	Average				96.4

In order to check this result more carefully, two series of experiments were carried out, in which a much larger difference in the oxygen content in the two cases was maintained. In each series four specimens were used, two being placed in tap water and the other two in a 10 per cent solution of sodium sulphate. In one series the liquids were first boiled down to about half their original volume in Erlenmeyer flasks to remove oxygen and the iron electrodes inserted during boiling. After the boiling an atmosphere of hydrogen was introduced into the flasks as they cooled down, so that practically no oxygen could have access to the liquid. In the other series air was caused to bubble through the liquid throughout the experiment, so that an abundant supply of oxygen was always present. The results are given in Table Va. From this table it will be seen that there is no appreciable difference between the efficiencies of corrosion in the presence of oxygen and in the absence of oxygen, at least in the liquid electrolytes here used. We have reason to believe, however, that this is not the case when the anodes are buried in soils, although just why a difference should exist here is not clear. That there is a difference is borne out by a number of tests we have made with anodes buried in earth in hermetically sealed cans and others buried in cans exposed to the atmosphere, conditions as to moisture content, current density, etc., remaining the same. Whenever the tests were continued for a considerable time, it was found that the efficiency of corrosion in the sealed receptacle was in nearly all cases considerably lower than when the container remained open. This effect is shown in Table 6.

TABLE 6

Corrosion Efficiencies in Open and Closed Cans

[Average current density, 0.494 milliampere per cm^2; area of anodes, 9.4 cm^2]

No.	Efficiency of corrosion		No.	Efficiency of corrosion	
	Closed cans	Open cans		Closed cans	Open cans
1	87.9	....	8	....	106.5
2	77.4	....	9	....	105.5
3	95.2	....	10	....	105.3
4	79.9	....	11	....	105.5
5	95.4	....	Average............	85.5	105.7
6	77.2	....			
7	85.8	....			

The average corrosion efficiency in the closed cans was 85.5 per cent, while that in the open cans was 107.5 per cent. Whether or not this difference is due to the difference in the amount of oxygen or CO_2 present or to other causes, it affords another indication of the danger of drawing conclusions from experiments made in liquid electrolytes as to what would occur in the case of electrodes buried in soils.

6. EFFECT OF OXYGEN ON THE END PRODUCTS OF CORROSION

One very marked effect of oxygen on corrosion, however, is its influence on the final products of electrolysis. There is a very common impression extant that the final products of corrosion of iron due to stray currents are the black oxids, whereas in the case of self-corrosion red oxids are produced. This is not in accord with accepted theories of corrosive processes, and the following experiments have been carried out in order to demonstrate that in general this is not the case, although under certain circumstances the tendency may be in that direction.

Four tests were made in which ingot iron was allowed to corrode naturally in the absence of oxygen, one test being in distilled water, two in tap water, and one in 10 per cent Na_2SO_4 solution. Four tests were made in which the iron was allowed to corrode naturally in the presence of oxygen, two tests being in distilled water and two in tap water. Four tests were made in which the iron was allowed to corrode electrolytically in the absence of oxygen, the electrolyte being tap water in two of the tests and 10 per cent Na_2SO_4 solution in the other two. Four tests were also made in which the iron was allowed to corrode electrolytically in the presence of oxygen, two tests being in tap water and two tests in 10 per cent Na_2SO_4 solution.

The solutions were prepared practically free from oxygen by boiling down to about half their original volume in Erlenmeyer flasks. The iron test pieces were introduced during the boiling, and after the boiling was stopped the flasks were closed off from the air and a current of hydrogen free from oxygen was allowed to pass into the flasks as they cooled down, thus keeping the solutions under an atmosphere of hydrogen.

In the case of the natural corrosion tests in the absence of oxygen, the iron showed no corrosion at first, but after a day or two a a few spots of greenish-black rust were noted, which gradually became larger as time went on, with the formation of a small amount of yellow ferric oxide. This was probably due to the fact that the air gradually diffused in through the rubber connections. In the case of the natural corrosion tests in the presence of oxygen, the rust was soon apparent and consisted almost entirely of the yellow ferric oxide. Thus we see that when oxygen is almost entirely excluded, the ferrous oxide predominates, and when oxygen is present, the ferric oxide predominates.

In the case of the electrolytic corrosion tests, the eight flasks were connected up in series, and a current of about 0.025 amperes allowed to pass for about 27 hours. At the end of this time the current was stopped and the anodes were taken out and weighed and the loss in weight determined. It was found that the corrosion efficiency was practically 100 per cent in all cases, calculating with iron having a valence of two. In the case of the four flasks from which air was excluded, the iron was practically all in the ferrous condition, the corrosion products having the pale green color of the hydrated ferrous oxide. Analysis of the corrosion products in one of the flasks gave 98.9 per cent ferrous iron, the slight oxidation being probably due to the unavoidable introduction of air into the flask during the removal of the electrodes for weighing. Through two of the other four flasks a current of air was allowed to bubble during the course of the electrolysis, and in those two flasks the corrosion products had the reddish-yellow color of the hydrated ferric oxide, showing that the iron was largely oxidized to the ferric condition. The other two flasks were left open to the air, but air was not bubbled through, and in these flasks the corrosion products had a darker color and when filtered off, dried, and tested with a magnet showed the presence of considerable magnetic oxide. Evidently then, the corrosion had proceeded so fast that there was not enough oxygen present to oxidize the oxide completely to the ferric condition, but in the other case, where air was bubbled through the solution, the solution was kept saturated with oxygen and so the oxide was converted completely to the ferric condition.

These results show that when iron corrodes electrolytically, it corrodes as the ferrous oxide, and that the formation of higher oxides is due to the oxidation of the ferrous oxide by the oxygen of the air, the degree of oxidation depending on the rate of corrosion and the concentration of the oxygen. If the rate of corrosion is relatively rapid and the concentration of the oxygen is relatively low, there will be predominance of the lower oxides, i. e., the ferrous oxide and the magnetic oxide. On the other hand, if the reverse is the case, i. e., if the rate of corrosion is relatively low, there will be a predominance of the ferric oxide.

The same explanation will apply to natural corrosion. In this case the rate of corrosion is very slow, and so the ferric oxide predominates; and even when the oxygen is almost entirely excluded, the rate of corrosion is so slow that there is a slight formation of ferric oxide, although the ferrous oxide predominates.

From the foregoing it will appear that the character of the end products of corrosion does not depend essentially on the cause of the corrosion, but that either of the oxides may be produced, both in the case of self-corrosion and in the case of electrolytic corrosion. It may, however, throw some light on the question in many circumstances, for the reason that the rate of natural corrosion of pipes embedded in earth may usually be expected to be so low that practically nothing but the ferric oxides would be produced, there being enough oxygen in the soil waters to oxidize any ferrous iron that may be formed. In the case of electrolytic corrosion, however, this will not always be the case, the corrosion being so rapid, especially under bad electrolysis conditions that the supply of oxygen in the ground waters will not be sufficient to oxidize all of the ferrous iron, and the result will be the formation of a considerable amount of magnetic oxide. This, however, will no doubt be largely affected by the depths of the pipe below the surface. The deeper the pipes, as a rule, the less would be the available supply of oxygen, and the greater would be the tendency for the formation of the magnetic oxide. Pipes very close to the surface even though corroding very rapidly by stray currents, might still form little, if any, magnetic oxide, because of the abundant supply of oxygen that would be available. Nevertheless, wherever a large preponderance of magnetic oxide exists, while it does not definitely prove that the corrosion has been due to stray currents, it may usually be regarded as a good indication that the rate of corrosion has been so great as to make it altogether probable that stray currents have been largely responsible, unless soil conditions, such as the presence of cinders, coke, chemicals, etc., are such that extremely rapid self-corrosion may be indicated.

7. RELATIVE ELECTROLYSIS IN DIFFERENT KINDS OF IRON

The question as to relative tendencies of different kinds of pipe to suffer damage due to electrolysis has often been discussed, and there appears to be a well-defined feeling in many quarters that a marked difference of this sort exists. It seems to be the general impression that cast-iron pipes are much less susceptible to electrolytic damage than wrought-iron or steel pipes. Experience indicates that cast-iron pipe does show less trouble from electrolysis than other kinds under most conditions. It has often been contended that certain kinds of iron are more resistant to self-corrosion than others, cast iron suffering less than either wrought iron or steel. Since the experimental data presented later in this paper show that the natural corrosion is affected in a marked degree by the presence of stray currents, it might reasonably be supposed that different kinds of pipes would also suffer in widely varying degrees from stray-current corrosion. In order to determine to what extent this might be the case, a considerable number of experiments have been carried out, using different kinds of iron that are employed in commercial service for underground pipes. Four kinds of iron were used, namely, ingot iron, which is the purest commercial iron known, wrought iron, machine steel, and cast iron. Two series of experiments were run on cast iron, in one of which the cast iron was machined to a clean surface and in the other the iron was used just as it came from the mold, without removal of the scale. The test specimens, weighing about 30 grams each, were placed in a red-clay soil practically saturated with water and run in series on a constant current, so that the same number of ampere hours was discharged from each test specimen. The results are shown in Table 7. Since the current in all specimens was the same, and the size of the test specimens practically the same, giving about 0.2 milliampere per square centimeter, the figures shown in the column under "electrical loss" are directly comparable for the different kinds of iron and show the relative tendency of the iron to corrode electrolytically under conditions of the test.

TABLE 7

Comparative Corrosion Efficiency for Ingot, Wrought, and Cast Iron, and Machine Steel

1. INGOT IRON

No.	Total loss	Self-corrosion	Electrical loss
	g	g	g
0	1.704	0.015	1.689
3	1.678	.033	1.645
4	1.848	.051	1.797
5	1.669	.031	1.638
6	1.791	.043	1.748
7	2.243	.046	2.197
8	1.665	.041	1.624
9	1.583	.074	1.509
10	1.688	.036	1.652
11	1.713	.060	1.653
12	1.706	.033	1.673
13	1.676	.042	1.634
14	2.167	.055	2.012
15	1.661	.028	1.633
16	1.679	.076	1.603
17	1.674	.046	1.628
18	1.648	.058	1.590
19	1.647	.057	1.590
Average		.046	1.695

TABLE 7—Continued

2. MACHINE STEEL

No,	Total loss	Self-corrosion	Electrical loss
	g	g	g
20	1.658	0.052	1.606
23	1.734	.076	1.650
24	1.827	.062	1.765
25	1.721	.066	1.655
26	1.672	.064	1.608
27	1.694	.076	1.618
28	1.684	.113	1.571
29	1.756	.087	1.669
30	1.644	.031	1.613
31	1.653	.046	1.607
32	1.792	.066	1.726
33	1.761	.059	1.502
34	1.686	.033	1.653
35	1.695	.063	1.632
36	1.808	.066	1.742
37	1.734	.066	1.668
38	1.818	.109	1.709
39	1.694	.059	1.635
Average		.066	1.652

3. WROUGHT IRON

40	1.713	0.160	1.533
43	2.203	.077	2.126
44	1.789	.065	1.724
45	1.712	.063	1.649
46	1.689	.117	1.572
47	1.842	.094	1.748
48	1.756	.116	1.640
49	1.693	.069	1.624
50	1.659	.048	1.611
51	1.201	.114	1.087
52	1.701	.124	1.577
53	1.661	.068	1.593
54	1.852	.055	1.797
55	1.684	.068	1.616
56	1.646	.050	1.596
57	1.712	.073	1.639
58	1.713	.076	1.637
59	1.840	.080	1.760
Average		.084	1.696

TABLE 7—Continued

4. CAST IRON SURFACED

No.	Total loss	Self-corrosion	Electrical loss
	g	g	g
60	1.807	0.120	1.687
63	1.700	.305	1.395
64	1.846	.108	1.738
65	1.757	.283	1.474
66	1.769	.177	1.592
67	1.746	.079	1.667
68	1.808	.136	1.672
69	1.939	.082	1.857
Average		.161	1.635

5. CAST IRON UNSURFACED

70	1.712	0.136	1.576
71	1.435	.255	1.180
74	1.810	.047	1.763
75	1.709	.060	1.649
76	1.868	.245	1.623
77	1.710	.135	1.575
78	1.662	.252	1.410
79	1.712	.060	1.652
Average		.149	1.553

An examination of these figures shows that there is but little difference in the amount of corrosion in the different kinds of iron. This is particularly true of the wrought iron, machine steel, and machined cast iron, which show, respectively, 1.641, 1.656, 1.635 grams loss. The ingot iron showed a somewhat higher electrolytic corrosion than any of the others, which seems to be somewhat surprising in view of the fact that it has frequently been found that the self-corrosion in the case of ingot iron is less than others. The least corrosion of all was in the case of the unfinished cast iron, and this is probably due to the protective effect of the scale, but even here the difference is hardly great enough to be considered of practical importance. The conclusion that must be drawn from these figures is that the efficiency of electrolytic corrosion of the different kinds of iron pipes is practically the same. If we examine the columns showing the self-corrosion in different kinds of iron we find very surprising differences. These check specimens were placed in the can along with the anodes and carefully shielded from the flow of current as in all previous cases. An examination of these data shows that ingot iron gave the least corrosion of all, the average for all the specimens being 0.046 grams. Machine steel came next with a total natural loss of 0.066 grams; wrought iron is third with 0.084 grams; and last, and most surprising of all, the self-corrosion of the cast iron is very much higher, being 0.161 for the machined iron and 0.149 for the unfinished iron. This shows but little difference between the finished and unfinished cast iron in the matter of self-corrosion in the presence of current flow. The relatively high rate of self-corrosion of cast iron as compared to the other kinds of iron tested is contrary to the generally accepted idea that cast iron is more resistant to self-corrosion than wrought iron. It is not improbable that this impression in regard to the superiority of cast iron has grown out of the fact that cast iron structures are usually made relatively heavy and they also tend to corrode more uniformly than wrought iron or steel, both of which factors would tend greatly to increase the life of the former. The principal cause of the greater rate of self-corrosion of cast iron appears to be the galvanic action set up between the free carbon and the iron. The carbon is distributed so uniformly throughout the mass, however, that no appreciable pitting results, and hence the corrosion is less conspicuous and also less important than the same amount of corrosion would be if not uniformly distributed as is usually the case of most other kinds of commercial iron. It should be pointed out here that these tests were carried out in the same kind of soil as that used in securing the data of Table 1, and the partial analysis there given shows it to be low in chlorides, sulphates, carbonates, and nitrates. It was also free from cinders, coke, etc., and hence is not to be regarded as a very corrosive soil. It is shown later in this paper that the chemical constituents in the soil have a marked influence not only on the total corrosion but also on the pitting, or uniformity of the corrosion, so that it should not be assumed that the relative values given here will hold for all soils.

The foregoing results show that the different kinds of iron do not in themselves differ materially as regards their tendency to corrode electrolytically. It would appear from this that the differences noted in practice, particularly in favor of cast iron, are due to various other causes, as has already been pointed out by Prof. Ganz and others, namely, higher resistance joints, higher specific resistance of the iron, the heavier walls, and a tendency to corrode more uniformly.

8. EFFECT OF CERTAIN CHEMICALS ON THE CORROSION OF WROUGHT IRON IN EARTH

When pipes are buried in the streets, they are subject not only to the action of the moisture and various natural constituents of the soil, but also to the effects of such chemicals as may result from the traffic on the streets, or from other sources.

A large amount of work has been done by other investigators on strips of iron immersed in aqueous solutions, and it has been shown that the resulting corrosion is a function of the amount as well as the character of the chemical used. In many cases the tendency toward self-corrosion first increases with the concentration and later diminishes very rapidly, possibly to zero, when the concentration is sufficiently increased.

It is well known also that certain solutions, such as alkalies, chromates, etc., tend strongly to inhibit electrolytic corrosion, at least when such solutions are practically pure. Hayden has shown that solutions of chromates, for example, tend to produce passivity in iron and thus prevent electrolytic corrosion, but that this passivity is destroyed by the addition of a few hundredths of 1 per cent of a chloride or a somewhat greater quantity of sulphate. It was considered advisable to carry out a series of experiments with iron embedded in earth to which various chemicals had been added.

For these experiments a number of acids, bases, and salts as indicated in Table 8 were secured and 2 grams of each were added to 300 g of distilled water. The solution was added to 700 g of air dried red clay, which had been sifted through a 20-mesh sieve. This earth contained initially about 5 per cent of moisture, so that the resulting mixture contained about 33 per cent water, which produced a fairly wet earth. The whole was thoroughly mixed and placed in a quart tin fruit can provided with friction top.

The anodes were prepared as in experiments already described and vessels of water were placed in the cans as in previous experiments and the cans connected in series; first, in one group; finally, on account of increased resistance, in three. The current was adjusted daily to 0.005 ampere, which gave a current density of discharge of about 0.45 milliampere per square centimeter.

At the end of 85 days the experiment was discontinued, the cylinders cleaned as previously described, and the losses computed.

In Table 8 the substances have been grouped according to the anions formed. Since in a number of cases more salt was used than the water could dissolve, the solubility of each chemical has been indicated. This is followed by the number of grams of the anhydrous salt used per liter of water. Then follows the chemical value of the solution, i. e., the number of grams of salt per liter of water multiplied by the hydrogen value of the anion and divided by the molecular weight of the salt.

TABLE 8

Effect of Chemicals on Corrosion

1	2	3	4	5	6	7	8	9	10
Chemical	Can No.	Solubility (g per liter)	Solution (g per liter)	Chemical value	Critical value (g per liter)	Limiting value (g per liter)	Efficiency of corrosion at (0.55 m. a. per sq. cm.)	Natural loss (Mg per sq. cm. per day) BS	Corrosion efficiency obtained by Hayden 1 per cent sol. (0.22 m. a. sq. cm.)
CH_3COOH	2	....	5. 715	0. 0957	....	....	102. 5	0. 109	....
$KMnO_4$	28	63. 4	5. 715	. 0364	0. 1	0. 1–1. 0	90. 2	. 166	....
$Ba (NO_3)_2$	34	92.	5. 175	. 0441	....	....	123. 2	. 150	....
$(NH_4) NO_3$	10	1924.	5. 715	. 0719	0–500	1155	116. 3	. 265	37. 8
$NaNO_3$	16	880.	5. 715	. 0677	. 1	632	104. 2	. 152	....
KNO_3	22	316.	5. 715	. 0571	....	....	89. 6	. 238	25.
HNO_3	4	....	5. 715	. 0914	....	....	85. 4	. 506	....
Average	....	....	....	....	....	....	103. 7	. 262	....

TABLE 8—Continued

1 Chemical	2 Can No.	3 Solubility (g per liter)	4 Solution (g per liter)	5 Chemical value	6 Critical value (g per liter)	7 Limiting value (g per liter)	9 Efficiency of corrosion at (0.55 m. a. per sq. cm.)	9 Natural loss (Mg per sq. cm, per day) BS	10 Corrosion efficiency obtained by Hayden 1 per cent sol. (0.22 m. a.) sq, cm.)
$BaCl_2$ (2 H_2O)	31	357.	4.874	.0479	0	374	106.0	.136	....
$CaCl_2$ (2 H_2O)	25	427.	2.890	.0526	....	....	101.8	.159	....
HCl	1	....	5.715	.1579	....	....	101.6	.270	....
NH_4Cl	7	372.	5.715	.1076	1.0	290	101.4	.496	102.3
KCl	19	340.	5.715	.0772	50.0	299	98.6	.222	102.2
NaCl	13	3582.	5.715	.0985	0	395	97.8	.239	....
Average	....	....	....	....	....	....	101.2	.253	....
Na_2SO_4 (10 H_2O)	18	194.	2.520	.0260	10.0	400	89.2	.136	....
K_2SO_4	24	111.	5.715	.0661	0	108	88.9	.170	102.8
$BaSO_4$	36	0.002	5.175	.0494	....	....	87.7	.231	....
H_2SO_4	6	....	5.715	.1174	....	....	87.4	.329	....
$(NH_4)_2 CO_4$	12	754.	5.715	.0873	0–200	534	86.0	.316	102.7
$CaSO_4$ (2 H_2O)	30	2.	4.520	.0669	0	....	85.9	.174	....
Average	....	....	....	....	....	....	87.5	.226	....
$Ba(OH)_2$ (8 H_2O)	32	39.	3.104	.0365	0	3.1	93.1	.322	....
NH_4OH	8	526.	11.770	.6965	....	....	88.7	.591	....
KOH (2 H_2O)	20	1120.	3.480	.0348	....	....	85.6	.611	....
NaOH (1 H_2O)	14	1090.	3.942	.0993	.1	1.0	81.7	.608	....
HOH (Av)	3 & 33	....	....	....	....	....	73.9	.268	....
$Ca(OH)_2$	26	1.6	5.715	.1556	0	.67–1.35	73.5	.195	....
Average	....	....	....	....	....	....	82.7	.431	....
K_2CO	21	1120.	5.715	.0834	1.0	1–10	89.3	.306	2.75
Na_2CO_3 (1 OH_2O)	15	275.	2.107	.0201	1.0	10	85.4	.394	....
$(NH_4)_2CO_3$	9	1000.	5.715	.1225	....	....	81.7	.561	38.2
$CaCO_3$	27	0.01	5.715	.0719	.0003	.28	66.2	.348	....
Average	....	....	....	....	....	....	80.6	.402	....
$BaCrO_4$	35	0.004	5.715	.0455	....	....	45.0	.189	....
$(NH_4)_2CrO$	11	405.	5.715	.0762	....	....	0.4	.003	....
$CaCrO_4$ (2 H_2O)	29	142.	4.643	.0640	....	....	0.3	.136	....
K_2CrO_4	23	632.	5.715	.0593	0	.1 up	0.3	.163	....
Na_2CrO_4 (10 H_2O)	17	813.	2.829	.0354	....	....	0.3	.082	....
CrO_3	5	657.5	5.715	.1143	0	.01–.05	−0.2	.122	....
Average	....	....	....	....	....	....	....	.116	....

Then follow two columns of values obtained from Hein and Bauer's "On the attack of iron in water and aqueous solutions." [5] The first is the concentration of solution giving maximum corrosion; the second the concentration producing passivity or minimum corrosion. Hein and Bauer suspended small iron plates in beakers of solutions of concentrations from zero to saturation. Their researches in this line are more extensive than any other work so far reported.

While their experiments can not be compared with the one now recorded on account of differences in conditions, the values quoted may indicate at what part of the corrosion-concentration curve the present tests were made, from which we may form some estimate as to the manner in which the corrosion would have changed if the concentration were varied. The efficiency of corrosion is given in the following column, and this is followed by the natural loss in milligrams per square centimeter of surface of the iron per day.

Referring to the efficiencies of corrosion given in column 8, it will be seen that with the exception of chromate compounds the efficiencies of corrosion are comparatively high.

All of the soluble chromates seem to protect the iron from electrolytic corrosion, though this protection is not quite complete. In the case of chromium trioxide the loss at the anode was slightly less than that of the check specimen. No significance should be attached to this result until after further investigation. The comparatively slight protection shown by barium chromate is no doubt due to its very slight solubility.

None of the other chemicals which Friend, Hein and Bauer, or Hayden have found to render iron passive in solutions seem to have been effective. Indeed, excepting the chromates there are but two values less than the average corrosion efficiency when distilled water was used.

The anodes in cans containing chromates were blackened, and making the iron cathode in 2 per cent H_2SO_4 for half an hour did not remove the discoloration. The check specimens were not discolored in this way.

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[5] Mittellungen aus dem Königlichen Material-prüfungsamt. 1908 Berlin 26, 1.

That the hydroxids did not protect the iron may have been due to the presence of materials in the soils which neutralized them. There was no doubt considerable CO_2 in the soil since it had been dried, crushed, and sifted in the laboratory and had stood there in an open barrel for some time, and this may have been sufficient to counteract the effect of the hydroxids.

As will be seen by comparing columns 4 and 7 the concentrations used in the case of the hydroxids and carbonates were in nearly every case greater than those producing passivity when the solution alone acts on the iron. The difference in the results may be due to the effect of the earth on the solution or to the effect of the current. It seems clear, however, that the conditions which prevent self-corrosion are not in general those which will maintain passivity in the case of anodes discharging current at moderate current densities. There does not appear to be any very definite relation between the corrosion efficiency observed and the self-corrosion. The nitrates and chlorides for instance show respectively 103 and 101 per cent efficiencies of corrosion with corresponding value of self-corrosion of 0.262 and 0.263 mg per square centimeter per day. The hydroxids and carbonates show lower corrosion efficiencies, namely, 82 and 80 per cent, respectively, but the natural corrosion is much higher, being 0.431 for the hydroxid and 0.402 for the carbonate. The soluble chromates show almost a complete absence of electrolytic corrosion, whereas the self-corrosion, although smaller than in the other cases, is by no means so small in proportion. It will be seen, also, that the corrosion efficiencies observed do not agree with the values found by Hayden,[6] and shown in column 10. While a part of this difference may be due to the differences in solution strength and current density, it is probably due for the most part to the fact that the tests in the present instance were carried out with anodes embedded in earth, whereas the experiments of Hayden were carried out in water solutions.

It does not seem probable that a sufficient quantity of inhibiting chemicals can be added to the soil surrounding a buried pipe to protect it indefinitely at a reasonable cost. To render the pipe

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[6] Jour. of the Franklin Institute, v. 172, p. 295.

passive is one problem; to maintain it passive against fluctuating, or even reversing currents regardless of the action of the soil and the constantly changing soil waters on the soluble chemical, is quite another.

A phenomena of importance which is not shown in the tabulated data, is the pitting of the iron. This is usually attributed to particles of impurities in the surface of the iron or to variations in the soil. In these experiments the virgin soil was dried, rolled, and sifted through a 20-mesh sieve. Enough solution was added to nearly saturate the soil. All of the cylinders were cut from the same piece of Norway iron rod. It might be expected, therefore, that the pitting would be very similar in all cases. This, however, was by no means the case. The anodes from the nitrate cans were covered by a dark cheese-like layer which maintained the original form of the anode. When this was pared off the surface of the iron was nearly smooth, showing the fibrous structure of the wrought iron but no pits. The anodes in the cans containing sulphates were corroded almost as uniformly; the surface of the cleaned anodes was brighter and somewhat uneven but showed no marked pits. The surface of the anodes from the carbonate cans was more uneven. Pitting is noticeable in the case of the hydroxids and very marked in anodes from the cans containing chlorids.

As has been stated the soluble chromates blackened the surfaces of the anodes but did not materially attack them otherwise. There are no marked differences in the appearance of the check specimens except that those from the chromate cans remained bright. So marked are the differences in the anodes that in most cases it is possible to classify them by their appearance without reference to their numbers.

As underground pipes are almost always destroyed by pitting rather than by the amount of iron lost, a satisfactory means of preventing pitting would be of great value. The remedy most commonly suggested is the use of a more homogeneous iron. Without doubt this would reduce the corrosion due to local galvanic action, but the above experiments indicate that pitting of buried iron is very largely influenced by the nature of the electrolyte in the soil.

It may seem that for comparing the effects of different chemicals quantities which are chemically equivalent should be chosen. A glance at columns 5 and 8 will show that in a number of cases practically equal corrosion efficiencies occur when the chemical values are very different. Indeed, so far as the tables go, there seems to be no relation between chemical values and corrosion efficiency.

It appears from these experiments that solutions which produce passivity when iron is immersed in them do not protect the iron against electrolytic corrosion when the solutions are in earth, and with the exception of the chromates, no chemicals here tried are of marked value in reducing corrosion. Also, the action of iron in a solution is not a safe criterion of its behavior when the iron is made anode in earth containing these solutions.

9. CORROSION IN SOILS FROM DIFFERENT SOURCES

While the foregoing experiments show the effect of the different factors which influence electrolytic corrosion in soils, it naturally raises the question as to what extent these various factors are acting in the case of iron pipes subjected to electrolysis under practical conditions. This question seems to be best answered by actually carrying out experiments on electrolytic corrosion in a great variety of soils of different kinds and gathered from widely different sources, at the same time maintaining the conditions as near to practical conditions as possible. In order to do this, corrosion tests were made on a large number of samples of soils which were gathered from various cities and sent to the Bureau of Standards at Washington for test as to their various physical properties. Ninety-seven such samples were used for these corrosion tests which were taken from various places in Philadelphia, Pittsburgh, Erie, and Apollo, Pa.; St. Louis, Mo.; Butte, Mont.; and Albuquerque, N. Mex. Practically all of these soil samples were taken from excavations made for the purpose of examining pipes and were taken at about the same depth as the pipe in most instances. In all cases the samples were put at once into hermetically sealed cans and kept therein until ready for test. For the purpose of making the corrosion tests the soils were divided into two classes. Those soils from Philadelphia, St. Louis, Butte, and Albuquerque were saturated with distilled water and kept so throughout the tests. The current density of the discharge averaged about 0.0002 ampere per square centimeter. The soils from Pittsburgh, Erie, and Apollo, Pa., were tested with the same moisture content which they had when taken from the ground, and the current density was maintained at about 0.001 ampere per square centimeter. We thus have for one set a very wet soil and a rather low current density, and in the other a rather high current density with what may be considered as roughly average moisture content, since at the time the samples were taken the soil was neither unusually wet nor unusually dry. The results of these efficiency of corrosion tests are given in Table 9. An examination of specimens 1 to 85, in which the earth was very wet and the current density low, shows quite high efficiencies of corrosion, the extreme ranges being 87.9 per cent for specimen No. 2 and 126.3 per cent for No. 30. All but four show values exceeding 100 per cent, while the great majority fall between 100 per cent and 115 per cent, the average of all being about 107 per cent.

TABLE 9

Corrosion Efficiency Tests on Soils from Different Sources

Rod No.[8]	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
	g	g	g	g	Per cent
1	2. 294	0. 114	2. 180	1. 867	116. 8
2	1. 811	. 170	1. 641	....	87. 9
3	2. 147	. 062	2. 085	....	111. 9
4	2. 244	. 195	2. 049	....	110. 0
5	2. 327	. 090	2. 237	....	119. 8
6	2. 203	. 117	2. 086	....	112. 1
7	2. 156	. 075	2. 081	....	111. 9
8	2. 244	. 175	2. 069	....	111. 0
9	2. 273	. 089	2. 084	....	116. 7
10	2. 363	. 133	2. 230	....	118. 8
11	1. 881	. 064	1. 817	....	97. 3
12	2. 103	. 174	1. 929	....	103. 4

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[8] Nos. 1 to 37, inclusive, taken from Philadelphia, Pa.; Nos. 38 to 47, inclusive, taken from Norristown, Pa.; Nos. 48 and 49 from Albuquerque, N. Mex.; Nos. 50 to 84 from St. Louis, Mo.

TABLE 9—Continued

Rod No.	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
	g	g	g	g	Per cent
13	2.173	.126	2.047	1.876	109.2
14	1.992	.025	1.967		104.8
15	2.052	.308	1.744		
16	2.584	.280	2.304		122.8
17	2.186	.041	2.145		114.4
18	2.207	.032	2.175		115.9
19	2.052	.086	1.966		104.8
20	1.804	.103	1.701		
21	2.058	.091	1.967		104.8
22	2.187	.130	2.057	1.871	109.9
23	2.168	.203	1.965		105.0
24	2.091	.044	2.047		109.4
25	2.220	.045	2.175		
26	2.239	.078	2.261		120.9
27	2.398	.112	2.286		122.3
29	2.091	.068	2.023	1.895	107.0
30	2.497	.108	2.389		126.3
32	2.190	.044	2.146		103.6
33	2.130	.079	2.051		108.4
34	2.068	.061	2.007		106.0
37	2.310	.170	2.140		113.2
38	2.114	.097	2.017		106.4
39	2.362	.085	2.277		102.4
40	2.375	.193	2.182		115.6
41	2.300	.025	2.275		120.2
42	2.313	.155	2.158		113.7
43	2.161	.150	2.011	1.913	105.0
44	2.148	.094	2.054		107.3
45	2.202	.031	2.171		113.4
46	2.105	.182	1.923		100.7
47	2.257	.101	2.156		112.8
48	2.489	.351	2.138		111.7
49	2.126	.022	2.104		110.2
50	2.177	.121	2.056		107.3
51	2.188	.122	2.066		107.9
52	2.305	.104	2.201		116.1
53	2.200	.148	2.052		107.3
54	2.250	.228	2.022		105.7
55	2.108	.052	2.056		107.4
56	2.330	.117	2.213		115.6
57	2.252	.115	2.137		111.7
58	2.206	.156	2.050		107.2
59	2.258	.247	2.011		105.2
60	2.194	.133	2.061		107.8
62	1.318	.054	1.264		66.2
63	2.201	.143	2.058		107.6

TABLE 9—Continued

Rod No.	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
	g	g	g	g	Per cent
64	2.242	.068	2.174	1.866	117.2
65	2.224	.157	2.067	...	116.3
66	2.295	.060	2.235	...	121.0
67	2.085	.045	2.040	...	109.9
68	2.164	.060	2.104	...	113.4
69	2.276	.181	2.095	...	112.9
71	2.225	.096	2.129	...	114.7
72	2.210	.156	2.054	...	110.8
73	2.152	.020	2.132	...	104.9
74	2.070	.096	1.974	...	106.4
75	2.190	.100	2.090	...	112.6
76	2.062	.038	2.024	...	109.2
77	2.200	.072	2.128	...	114.6
78	2.089	.151	1.938	...	104.4
79	2.063	.114	1.949	...	105.1
81	2.286	.064	2.222	...	119.8
82	2.152	.157	1.995	...	107.5
83	2.330	.135	2.195	...	108.3
84	1.706	.188	1.518	...	81.8
85	2.062	.003	2.059	...	111.0

PITTSBURGH, PA., SOILS

Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
g	g	g	g	Per cent
4.600	0.207	4.393	4.969	88.4
5.100	.177	4.923	...	99.2
3.953	.295	3.658	...	74.7
2.780	.220	2.560	...	51.6
5.210	.030	5.180	...	104.3
4.368	.005	4.363	...	87.8
5.195	.140	5.055	...	101.6
2.822	.270	2.552	...	51.4
3.005	.140	2.865	...	57.7
4.435	.145	4.290	...	86.4
3.519	.546	2.973	...	67.2
4.272	.545	3.727	...	72.0

ERIE, PA., SOIL

4.932	0.185	4.747	4.750	99.9
3.499	.250	3.249	...	68.2
4.692	.255	4.437	...	94.0
3.595	.129	3.466	...	72.9
4.777	.245	4.532	...	74.4
18.180	1.451	17.729	...	80.7
7.531	.040	7.491	...	36.3

Current density, 1 milliampere per square centimeter.

The figures in the second group show much lower values, the extreme range being between 36.3 per cent and 104.3 per cent. Most of the values fall between 60 and 100 per cent, with an average for all specimens of about 76 per cent. The difference between the efficiencies of corrosion shown by the two series is evidently due partly to the lower moisture content and higher current density in the latter case. These results are in accord with the data already presented in which the effects of moisture and current density have been studied separately. It should be pointed out here that while the current density in the second series is higher than may be expected under average conditions in practice, it is no higher than would frequently be encountered under moderately severe practical conditions. From these and the preceding tests it will be evident that under average practical conditions we may expect the corrosion efficiency to be of the order of 100 per cent when the earth is very wet and the current density quite low, while as the moisture content is reduced or the current density increased the corrosion efficiency falls off and will usually be found to range between 50 and 100 per cent, while in quite dry soils, such as might at times be encountered in practice, a much lower figure might occur. We are convinced that under average conditions of soil moisture, and with current densities that may be expected in localities where electrolysis conditions may be considered moderately severe, a corrosion efficiency between 50 and 110 per cent will usually prevail. It will be seen also from the foregoing data that the decrease in corrosion efficiency due to increased current density is by no means as rapid as the increase in current, so that within the limits of current density that will usually be encountered in practice the actual amount of corrosion will be found to increase with increase of current.

The question may well be raised as to the reliability of corrosion efficiency experiments carried on in earths in the laboratory, and the extent to which such results may be considered as representing what would take place in the earth under normal conditions. In general, however, it will appear that experiments made in the laboratory are much more satisfactory for studying the laws of corrosion because conditions can then be much more readily controlled, and it is simply necessary to determine whether or not the laws of corrosion are substantially the same in the case of experiments on iron embedded in small samples of soil as they would be if the iron were embedded in the earth out of doors, all other conditions being the same. This would probably not be true if the experiments were continued over a great length of time during which certain soluble constituents of the soil in the laboratory specimens might become exhausted by the corrosive processes, but we have ample reason to believe that experiments thus made and extending over a comparatively short time represent quite closely what may be expected to take place in the case of pipes under actual conditions. Numerous experiments have been made on specimens of iron embedded in the earth out of doors in order to check this conclusion and to guard against any serious error that might be introduced by possible conditions of the soil. Some of the data bearing on this have already been given in the earlier part of this report relating to the effects of depth of burial and of current density on efficiency of corrosion, which show that for similar conditions the results for the outdoor tests do not give results materially different from the laboratory tests. Another series is given in Table 10. In this case a number of specimens of iron were buried in the earth out of doors and caused to carry current for several months, and the efficiency of corrosion was determined. The current density varied considerably during the experiments, due largely to change in resistance of the soil, but on the whole the range of current density averaged about the mean of the values used in the tests on effect of current density given above. The moisture content, of course, varied considerably from time to time.

An examination of Table 10 shows that the efficiencies of corrosion in these outdoor tests ranged between approximately the same limits as those carried on indoors for similar ranges of moisture and current density. These data afford additional evidence that the results of the corrosion efficiency experiments carried on on samples of iron embedded in soils in the laboratory are of substantially the same order of magnitude as they would be if the iron had been buried out of doors.

TABLE 10

Efficiency of Corrosion, Specimens Buried in Ground out of Doors

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
	g	g	g	Per cent
1	15. 719	0. 286	15. 433	74. 9
3	12. 159	. 286	11. 873	72. 8
5	4. 425	. 282	4. 143	61. 5
6	5. 879	. 282	5. 597	73. 9
7	5. 894	. 280	5. 614	80. 0
10	6. 374	. 280	6. 094	96. 3
11	2. 364	. 278	2. 086	83. 3
12	3. 310	. 278	3. 032	76. 8
Average..	....	....	....	77. 9

10. CAUSES OF VARIATIONS IN EFFICIENCY OF CORROSION

The causes which give rise to corrosion less than the theoretical amount according to Faraday's law have been the subject of much investigation by numerous investigators in connection with studies of passivity in iron. Numerous theories have been evolved, but comparatively little is definitely known in regard to this subject. The subject is too complicated and would lead to too much theoretical detail for discussion here. On the other hand, no attention has been given to the influences that may be responsible for corrosion efficiencies greater than 100 per cent, and in view of the frequency with which these high efficiencies of corrosion occur it seems well to present here very briefly a few comments as to the possible causes that may be responsible for these high values.

It has been seen that the efficiency of corrosion of iron embedded in earth in many cases exceeds 100 per cent, although we have not been able to confirm the results of other investigators previously referred to in this paper who have reported electrolytic corrosion amounting to several times the theoretical value. The highest values which we have found in our experiments have been of the order of 150 per cent, but for the most part the corrosion has not been greater than 20 per cent in excess of the theoretical amount. The very large number of cases, however, both among the tests already described and among those that follow, in which the corrosion efficiency exceeds 100 per cent, even after careful correction has been made for self-corrosion, indicate quite clearly that the loss of iron due to the discharge of electric current is in many cases appreciably greater than the theoretical amount. This is a matter of great importance and is being given special attention with the view of throwing further light on its causes, but much yet remains to be done before the phenomena can be properly understood.

Several causes suggest themselves as possible factors in producing this high efficiency of corrosion, some of which are discussed below.

(a) **Formation of New Galvanic Couples.**—It is well known that when iron corrodes in the presence of water and oxygen oxids of iron are formed as end products. Under most underground conditions these will be deposited at the surface of the iron in more or less irregular contact with the iron. These oxids are fairly good conductors and are also electronegative against iron, so that when a particle of iron oxid comes in actual contact with the iron, a galvanic element is formed which tends to corrode the adjacent iron. It seems not improbable, therefore, that when a clean piece of iron is subjected to the discharge of electric current the formation of the iron oxid which results from the initial corrosion may set up galvanic couples which did not before exist and thus greatly increase the self-corrosion on the specimen.

The following experiments were carried out to gain an idea of the effect of the initial corrosion products on subsequent electrolytic corrosion and on the self-corrosion of the specimen. In this experiment twelve 2-quart tin cans were coated outside with paraffin, and a layer of heavy paraffined paper placed over the sides. The cans were then nearly filled with red clay which had been air dried two months and sifted through a 20-mesh sieve; 300 g of distilled water was added to 700 g of this sifted earth, and the whole thoroughly mixed before it was packed in the cans. This earth was nearly saturated with water. For anodes and check specimens cylinders of ¼ inch Norway iron 2 inches long were used. The cylinders were carefully cleaned and placed vertically in the cans, the anodes in the center and the check specimens close to the side, and carefully shielded from current flow. A small vessel of water was placed within each can to retard evaporation of the moisture in the earth.

The 12 cans were then connected in series on a 115-volt circuit; the cans serving as cathodes. The current was kept practically constant at 10 milliamperes.

At the end of 429 hours 8 cans were removed from the circuit. Four of these were set aside unopened. From the other four the cylinders were removed, cleaned, weighed, and replaced, and the 4 cans were then replaced in circuit.

At the end of 686 hours more the cans were opened, the cylinders cleaned, weighed, and the losses computed. When the cylinders were washed in warm water, practically all of the rust came off, so that it was necessary to clean them electrolytically for but a few minutes to obtain a bright surface.

The corrosion of the anodes was more uniform than in most previous experiments, but the corroded surface was nevertheless somewhat uneven, the loss being greatest near the centers of the cylinders. There was practically no pitting of the check specimens.

The results of the experiments are shown in the following Table 11:

TABLE 11

Effect of Initial Products on Subsequent Corrosion

Area of exposed metal, 7.6 cm²; current density, about 1.2 milliamperes per cm²; moisture in soil, about 30 per cent]

GROUP A

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
	g	g	g	Per cent
2	4.270	0.085	4.185	102.8
6	4.408	.085	4.323	106.3
7	4.365	.085	4.280	105.2
12	4.370	.085	4.285	105.3
Average......	....	....	....	104.8

GROUP B, FIRST PERIOD

1	4.230	0.045	4.185	102.8
3	4.226	.045	4.181	102.7
13	4.225	.045	4.180	102.7
14	4.273	.045	4.228	103.8
Average......	....	....	....	103.0

TABLE 11—Continued

GROUP B, SECOND PERIOD

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
	g	g	g	Per cent
1	6.316	0.080	6.236	87.8
3	6.645	.080	6.565	92.5
13	6.475	.080	6.395	90.1
14	6.823	.080	6.743	95.0
Average				91.4

GROUP C

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
4	11.185	0.149	11.036	99.0
5	10.658	.149	10.509	94.3
8	10.275	.149	10.126	90.8
9	10.945	.149	10.796	96.9
Average				95.2

Here the specimens are divided into three groups—A, B, and C. In group A the current was kept on the specimens during the first period of 429 hours and then switched off, but the specimens were permitted to stand in the soil undisturbed during the second period of 686 hours, after which they were taken out and weighed and the efficiency of corrosion determined. In this case if the initial corrosion due to the electric current tended to accelerate self-corrosion we should expect a higher efficiency of corrosion than if the specimens had been removed as soon as the current was shut off. In group B the specimens also carried current during the first 429 hours, but were removed from the earth, cleaned, and weighed as soon as the current was shut off, and then put back in circuit again. If the self-corrosion is greater due to the initial electrolysis, we should expect that the efficiency of corrosion would be smaller for the first period in group B than was obtained for group A. The table shows that such was the case, although the difference is quite small and may possibly be due to other causes. By cleaning these specimens and putting them back in the same soil in which they had previously run and maintaining the same current flow as before during the second period we could determine whether there was any marked change in the efficiency of corrosion due to changes in the soil caused by the flow of current. The table shows that there was a marked difference here, the efficiency of corrosion being much lower during the second period than during the first. In group C the specimens were permitted to remain in circuit during both the first and second periods without interruption.

In comparing the results obtained from these three groups it is significant that the highest apparent efficiency of corrosion was obtained when the current was allowed to flow for a time and then removed and the specimen allowed to remain in the earth subjected to the action of self-corrosion during the second period. The next largest apparent efficiency was obtained when the specimens were cleaned and weighed at the ends of the first period immediately after the stopping of the current. The lowest efficiency was obtained when the cleaned specimens of group B were returned to the same earth which had been previously used and again connected in circuit during the second period. Further, group C, which ran continually throughout the first and second periods, showed an intermediate value of corrosion efficiency. These results appear to show that there are two opposing tendencies at work, one of which is to increase the corrosion efficiency, as in group A, due to some cause associated with the flow of current, and the other a tendency to decrease the corrosion efficiency, as in group C, due perhaps to depletion of certain ingredients in the electrolyte. Other experimental data given in this paper indicate that this tendency for the efficiency of corrosion to decrease with time may be due either to the exhaustion of dissolved oxygen or to a loss of moisture by the earth.

The check specimens used in these experiments also show the effect of current flow on the self-corrosion of check specimens placed in the cans along with the anodes. Examining the data for group B under the column headed "Self-corrosion," we find that during the first period the rate of corrosion was less than after the check specimens had been cleaned and returned to the same cans. By comparing the self-corrosion in group A with those in groups B and C the tendency is seen to be the same and even more marked. Further, by comparing the self-corrosion of group B with that of group C we find that, although the total flow of current is the same, the corrosion is considerably greater in the latter. Since those of group B were removed once and cleaned, while those of group C were not, this result seems to support the theory that the presence of a small amount of initial corrosion tends to stimulate the self-corrosion throughout the remaining period of the test. It should be borne in mind, however, that the figures on which this statement is based are subject to such large variations that they should not be accepted as conclusive until they have been repeatedly verified.

(b) **Depolarizing Effect of Oxygen.**—According to the electrolytic theory of corrosion all iron contains sufficient differences in physical or chemical structure at different points on its surface to set up local galvanic elements which are supposed to be responsible for self corrosion. Under ordinary conditions of self corrosion, therefore, there will be certain points on the surface which will be anode points discharging current into the electrolyte and corroding the iron, and there will also be near by cathode points at which the current reenters the iron. The amount of corrosion which results from these couples will, of course, depend upon the resistance of the local circuit as well as on the effective difference of potential which exists between adjacent points. When current flows in these local paths there is a tendency to form a film of hydrogen at the cathode points which diffuses but slowly, and this not only sets up a counter electromotive force, but it likewise introduces a large amount of additional resistance into the local circuit. In consequence of this the self corrosion may be said to inhibit itself to a very considerable extent. If now we superpose on this specimen an electric current, making the specimen anode, more or less oxygen will be liberated near the surface of the metal which may react with the hydrogen, thus in effect depolarizing the local galvanic elements and permitting much greater self corrosion in the case of a specimen discharging current than in a case of a similar specimen not discharging. This excess of self corrosion would always appear due to the main current flowing and would thus increase the apparent efficiency of corrosion. It is easy to see how this effect could increase the efficiency of corrosion from a low value up toward 100 per cent, although it would not in general tend to make the corrosion efficiency greater than 100 per cent.

(c) **Nonuniform Corrosion of the Iron.**—When iron corrodes it is always with greater or less irregularity. Pits may be formed in which a small hole on the surface may communicate with a large chamber below, and this pitting may pursue such an irregular course as to eat entirely around particles of iron, causing them to fall away from the test specimen. This seems particularly likely to happen in the case of very impure metals, which often exhibit a more or less honeycombed aspect after long-continued corrosion. Since the efficiency of corrosion is always determined from the net loss of weight, any particles of iron that might be dislodged in this manner would be charged against the current, and in this way the corrosion efficiency might easily be made to appear larger than 100 per cent.

(d) **Circulation of the Electrolyte.**—It is well known that if the electrolyte surrounding a piece of iron be kept in constant circulation, the amount of self corrosion which results will be greater than if the electrolyte remains practically still. When an electric current flows through an electrolyte it causes a migration of the ions, which may increase the self corrosion of the iron in a manner analogous to circulation of the electrolyte. Particularly, in the case of an anode there is a tendency for the acid radicals such as Cl, SO_4, etc., to concentrate near the anode surface, and it is well known that liquids containing large amounts of these radicals, particularly the chlorine, produce very rapid corrosion of the iron. Here, again, any excess of self corrosion which would be produced would be charged against the electric current, and a high efficiency of corrosion would result. It is not improbable that any or all of the above-mentioned causes may be operating in certain cases to produce a high efficiency of corrosion. However that may be, it has been definitely established that if a check specimen is embedded in the earth along with the anode the self corrosion will always be much higher than if the check specimen is embedded in the same earth but in a separate vessel. This is true even when ample precautions are taken to shield the check specimens from the flow of electric current. This is shown by the following series of experiments, which is typical of a great many which have been carried out. The anodes were buried in the center of a quart tin can filled with earth, the can itself serving as the cathode. The check specimen was placed in the earth near the cathode and shielded from current flow by means of a glass shield, semicylindrical in form and of considerably greater diameter and length than the check specimen. The arrangement is shown in Fig. 1. In many of these experiments, in addition to the check specimens placed inside the can, a second check specimen was also placed in the same kind of earth with the same moisture content, but placed in a separate vessel, through which no current passed. A few of these data, which are typical of all, are given in Table 12.

TABLE 12

Effect of Current Flow on Self Corrosion

Check No.	Loss of check with iron carrying current 49 days	Loss of check in separate vessel 83 days	Check No.	Loss of check with iron carrying current 49 days	Loss of check in separate vessel 83 days
	g	g		g	g
7	0.075	0.041	63	0.143	0.063
14	.025	.022	83	.135	.018
21	.091	.025	84	.118	.014
28	.038	.022			
35	.048	.045	Average..	.092	.034
42	.155	.057			

From this table it will be seen that the average self-corrosion on the check specimens placed in the can carrying current was roughly 2.7 times that on the specimens in the cans through which no current passed, while the time in the latter case was 1.7 times that in the former, thus making the average rate of self-corrosion about 4.6 times as great in the can carrying current as in the one which carried no current. Further, it seems altogether probable from the foregoing discussion of causes of increased corrosion efficiency that the self-corrosion on the anode itself would be considerably greater than that on the check specimen placed inside the same can, so that even though the electrolytic corrosion proper were to take place strictly in accordance with Faraday's law we should nevertheless obtain an experimental result indicating an efficiency considerably greater than 100 per cent.

In view of the foregoing, therefore, it does not appear that we have any reason to suppose that the electrolytic corrosion proper does not take place in accordance with Faraday's law, even though a corrosion efficiency of much more than 100 per cent is indicated. Nevertheless, in computing corrosion efficiency it is proper to charge all of this excess of self-corrosion against the electric current, since in the absence of the current it would not have occurred, and the corrosion directly chargeable to the current includes all of that which results from the passage of the current, whether due directly to the current or to secondary causes brought into action by the current flow.

11. EFFECT OF VERY LOW VOLTAGE

In all of the foregoing experiments, although the current density has often been reduced to quite low values, the voltage impressed upon each pair of electrodes has in general been somewhat high, being of the order of several volts in most instances. This has been due to the fact that the small size of most of the electrodes used gave rise to so high a resistance in the earth that voltages of this order were necessary in order to produce the desired current density. Although there is no theoretical reason why the efficiency of corrosion should vary with voltage, except in so far as it affects the current density, nevertheless it seemed very desirable to carry out a few experiments on very low voltages, particularly below 1 volt, in order to determine whether the efficiency of corrosion would be materially different with such extremely low voltages from what it is on the higher values. Accordingly three cells were made up using tap water as an electrolyte and thin sheet-iron electrodes separated by several sheets of filter paper. This gave very low resistance between the electrodes and made it possible to secure sufficiently large current on much lower voltages than had been possible in the case of specimens buried in soil. One of these cells was run on a constant potential of 0.1 volt, another on 0.6 volt, and the third at 1 volt. Current measurements were made at frequent intervals and the ampere hours determined. The results are shown in the table following.

TABLE 13

Low Voltage Test

[Area of anode, 47.47 square centimeters; average natural loss of anode, 40 mg]

Plate No.	Loss total	Electrical loss	Theoretical loss	Corrosion efficiency	Current density (mil. amps./cm²)	Voltage
1	0.496	0.456	0.467	97.7	0.051	1.0
2	.153	.113	.127	89.0	.014	.6
3	.062	.022	.024	91.7	.003	.1

It will be seen by reference to this table that the efficiencies of corrosion are comparatively high, being highest in the case of the 1-volt cell and lowest in the case of the 0.6-volt cell and intermediate in the case of the 0.1-volt cell. The current densities are given in the table and are seen to be extremely low, the lowest being but 0.003 of a milliampere per square centimeter. These results show quite clearly that there is no reason to expect that the corrosion efficiency changes materially at any critical value of voltage within a range that is of any practical consequence in the negative return of street railway systems.

III. EARTH RESISTANCE

The foregoing experiments show what may in general be expected under different conditions as to the discharge of current from iron electrodes buried in soils. In practice, however, when investigating electrolysis conditions, we are not dealing with known conditions of current flow, since it is in most cases impracticable to measure directly leakage currents at any point in the soil without resorting to measures that are too tedious and expensive for most work. We have, on the contrary, certain easily determined voltage conditions throughout the negative railway return system, and hence, in order to properly interpret the data above presented relating to laws of corrosion, it is necessary to take into consideration the effect of earth resistance on the stray currents that may be carried by the pipes and discharged by them into the earth under known conditions as to potential differences in the network. It is not the purpose of this paper to go into detail in regard to the matter of earth resistance, as this is to be treated somewhat fully in another paper by the authors in a publication of the Bureau of Standards. The great importance of the subject of earth resistance, however, in relation to electrolytic corrosion in soils makes it desirable to present here very briefly a few fundamental principles in regard to the resistance of soils and its relation to stray-current electrolysis.

It is obvious that if the soil surrounding the pipe network possessed infinite resistance there would be no trouble from electrolysis, since in that case no stray current could leak off of the tracks and hence find its way into the pipes. On the other hand, if the earth possessed zero resistance, we would also have no electrolysis, since in that case the earth would short circuit the pipes and prevent them from taking up the stray currents. Somewhere between these two extremes we will obviously have a value of earth resistance which in any given case would produce a maximum of electrolysis trouble. The value of this resistance required to give a maximum electrolysis undoubtedly varies greatly with conditions, such as geometrical form of the pipe and track networks, kinds of joints used in pipes, size of pipes, resistance of rail return, and numerous other factors. We feel confident, however, from observations made under practical conditions that in most if not all cases the resistance of the earth will be found much higher than that required to produce maximum electrolysis, so that in general we may expect the electrolysis to be greater the lower the resistance of the earth. With a view of giving an idea of what may be expected in the way of earth resistance in practice, we present below a summary of some investigations which we have made in regard to variation of earth resistance with varying conditions, and following that we have given the results of a considerable number of earth-resistance measurements made on a variety of soils taken from widely scattered sources. In making these earth-resistance measurements several different methods were used, in some of which the earth was measured in place without being disturbed, while in other cases the samples were taken to the laboratory, packed in glass cylinders, and the resistance measured between plastic amalgam electrodes pasted on the ends of the cylinder, the voltmeter-ammeter method with alternating current being used. In a good many cases both methods were used and the results were found to check in a very satisfactory manner. In making the earth-resistance measurements in place two excavations were made side by side to a depth of several feet, leaving a portion of undisturbed earth several inches in thickness between the two excavations. The sides of this undisturbed portion were made approximately parallel and fairly smooth, and small electrodes a few inches in diameter placed on the opposite sides. These electrodes were then surrounded by guard rings of sufficient diameter to assure practically parallel lines of current flow between the two electrodes. The resistance of the earth between the electrodes was then measured by means of the voltmeter-ammeter method as in the laboratory, alternating current being used for the purpose. In making these measurements care was taken to keep the electrodes and the guard rings not only at the same potential, but also to see that there was no displacement of phase between the emf's applied to them.

In making the tests in the laboratory preliminary experiments showed that much more satisfactory results could be obtained by compressing the earth in the testing machine to such a point that further increase in pressure caused practically no variation of resistance. It was found, and will be shown by the curves below, that with increase of pressure a point is soon reached beyond which the resistance varies but slightly with further increase in pressure. Careful comparison of results obtained by first measuring the resistance in place in the ground, and later in the same earth in the laboratory, indicated that they were practically the same whichever method was used, and since the method of measuring the resistance in the laboratory was so much more rapid and convenient this method was used for the great majority of of measurements that are presented below.

1. EFFECT OF MOISTURE CONTENT ON EARTH RESISTANCE

Moisture content is one of the controlling factors in earth resistance. In Table 14 are given a series of resistance measurements taken on a sample of red-clay soil with varying moisture content, which may be regarded as more or less typical.

TABLE 14

Relation Between the Amount of Moisture in the Soil and its Specific Resistance

Per cent moisture (in terms of dry earth)	Specific resistance (ohms per centimeter cube)	Per cent moisture (in terms of dry earth)	Specific resistance (ohms per centimeter cube)
5.0	2 340 000	44.5	4725
11.1	237 400	55.6	4870
16.7	13 880	56.7	5197
22.2	6835	77.8	5045
33.3	5400		

For making each measurement a new sample of thoroughly dry earth, dried at 105° C, was taken and the required amount of moisture added, the percentage of moisture being expressed in terms of the dry earth. It will be seen that above about 22 per cent of moisture the resistance remains practically constant, but below this value the resistance rises very abruptly with decrease of moisture content, and at 5 per cent of moisture the resistance has risen to considerably over 400 times its value when the soil is saturated. This shows that the actual current flow to and from a pipe embedded in soil is dependent in vastly greater degree on the moisture content than on the potential difference between the pipe and surrounding structure, and points to the fact that a potential difference which might be perfectly safe in a high and well-drained locality might be sufficient to give rise to a great deal of damage in a low and damp locality. This tendency has of course been well recognized, but it has not been given the consideration which it deserves. Cases frequently arise in which this fact might well be treated as an important factor in determining the location of a railway substation, and particularly the points at which insulated radial return feeders might best be connected to the tracks.

Another important practical aspect of this change in resistance with moisture content is its effect on the distribution of potential drops throughout the negative railway return area. Since the various parts of the pipe systems are buried at different depths and are very irregularly located with respect to the tracks, it is evident that changes in the moisture content with depth will exert a marked influence on the distribution of the resistance in the path of the leakage current, which in turn will greatly affect both the magnitude and distribution of the potential gradients throughout the system. For this reason not as much reliance should be placed on voltage surveys made at extremely wet, and more especially at very dry periods, as on those taken under more nearly average moisture conditions.

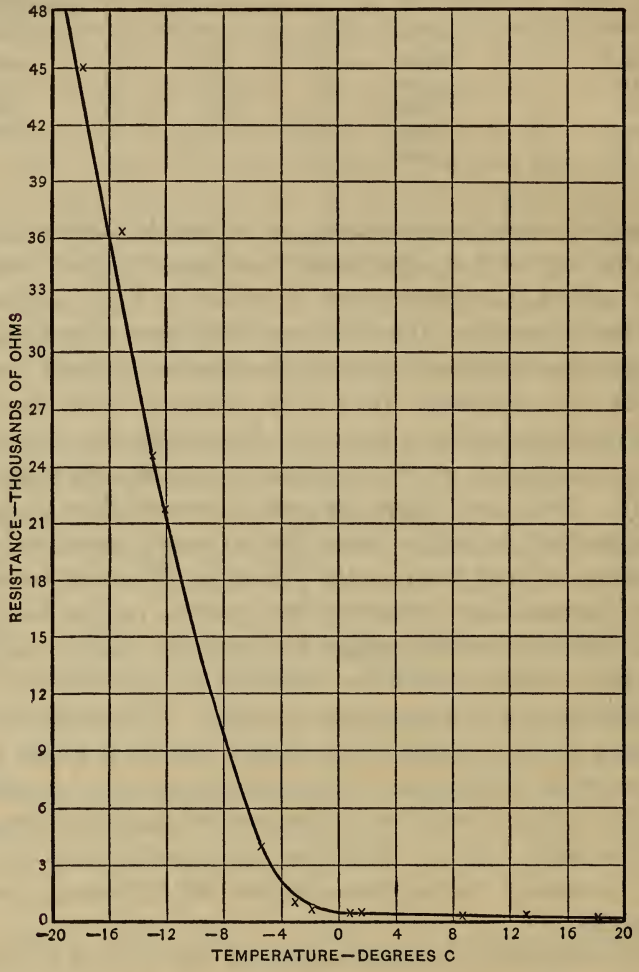

Fig. 8.—*Effect of Temperature on Earth Resistance*

2. EFFECT OF TEMPERATURE ON EARTH RESISTANCE

The effect of temperature on the resistance of soil was determined throughout the range from about 18° C to −18° C (0 to 65° F). For this purpose a moist soil was used and was placed in a vessel surrounded by an ice chamber in which a mixture of ice and salt was placed, and the whole was allowed to stand until the temperature had reached about −18° C, the resistance being measured from time to time by means of electrodes which were embedded in the sample of earth and brought out by rubber-covered leads. The temperature of the earth was taken at the same time each resistance measurement was made, an ordinary mercury thermometer inserted in the center of a hollow electrode being used. The results of these resistance measurements as a function of temperature are given in Table 15 and are plotted in Fig. 8. By reference to the curve it will be seen that the resistance varies throughout very extreme ranges, even within the ranges of temperature variation that commonly occur in this country. Above freezing the resistance variation is much less marked, but even here we find that the resistance at 0° C is is approximately 2½ times its value at 18° C. At about the point at which the soil water begins to freeze there is a tremendous increase in the temperature coefficient of resistance, and as the temperature becomes lower the resistance rises enormously, and at −18° C the resistance is seen to be over 200 times as great as at 18° above zero.

TABLE 15

Effect of Temperature on Resistance of Soil

[Soil No. 32; moisture, 18.6 per cent; specific resistance at 20°, 6260 ohms/cm^3]

Temperature	Resistance	Temperature	Resistance
°C	Ohms	°C	Ohms
18.0	224	− 3.0	1185
13.0	286	− 5.5	4340
8.5	398	−12.0	21 700
1.5	458	−13.0	24 600
1.0	462	−15.0	36 200
0.0	542	−18.0	45 000
−2.0	940	−19.0	48 900

This enormous variation of earth resistance with temperature is of considerable practical importance and indicates that in moderately cold weather such as prevails in the northern cities comparatively little trouble from electrolysis may be expected. This is due not primarily to the higher resistance of the earth immediately surrounding the pipes, since the pipes are usually located at a sufficient depth so that the temperature of the earth immediately surrounding will not reach the lower values used in this experiment. The real reason for the diminution of electrolysis trouble with the fall in temperature is the reduction of leakage current from the rails. It will be evident that when the ground is frozen even but a few inches deep the resistance of the earth immediately surrounding the rail is enormously increased, and the leakage of stray currents into the earth is thereby correspondingly reduced. And since the rise in resistance with even a few degrees of frost may be manyfold, it is apparent that but a thin layer of frozen earth about the rail would be necessary in order to produce a very marked increase in the total resistance of the path of the leakage current. This reduction in electrolysis troubles in cold weather due to increase in resistance of the earth is further augmented by the increase of the conductivity of the rail return which takes place at the lower temperature, which may amount to as much as 15 or 20 per cent, and is sufficient as a rule to compensate for the increased load which usually prevails during the cold period.

It should also be pointed out here that the effect of variations in temperature with depth on the resistance of earth will have an effect on the distribution of potential gradients in the earth very similar to variations in moisture content referred to above. For this reason it is preferable not to make voltage surveys at times when extremely low temperatures prevail.

3. EFFECT OF MECHANICAL PRESSURE ON EARTH RESISTANCE

Of considerable interest, although of much less practical importance, is the effect of mechanical pressure on the electrical resistance of earth. As already stated, when pressure is applied to a sample of earth its resistance is but little affected, as a rule, after a certain relatively low value of pressure is reached. This is shown in Fig. 9, which gives resistance-pressure curves for a number of different soils from various sources. The range of pressures here are for the most part between 20 and 1000 pounds per square inch, and the variations in resistance between these limits are surprisingly small. Numerous measurements of the resistance of earth 2 or 3 feet below the surface before being disturbed, using the guard-ring method, and subsequent measurements of the same earth in the laboratory under pressure show that the resistance at a few hundred pounds' pressure per square inch is substantially the same as the undisturbed earth.

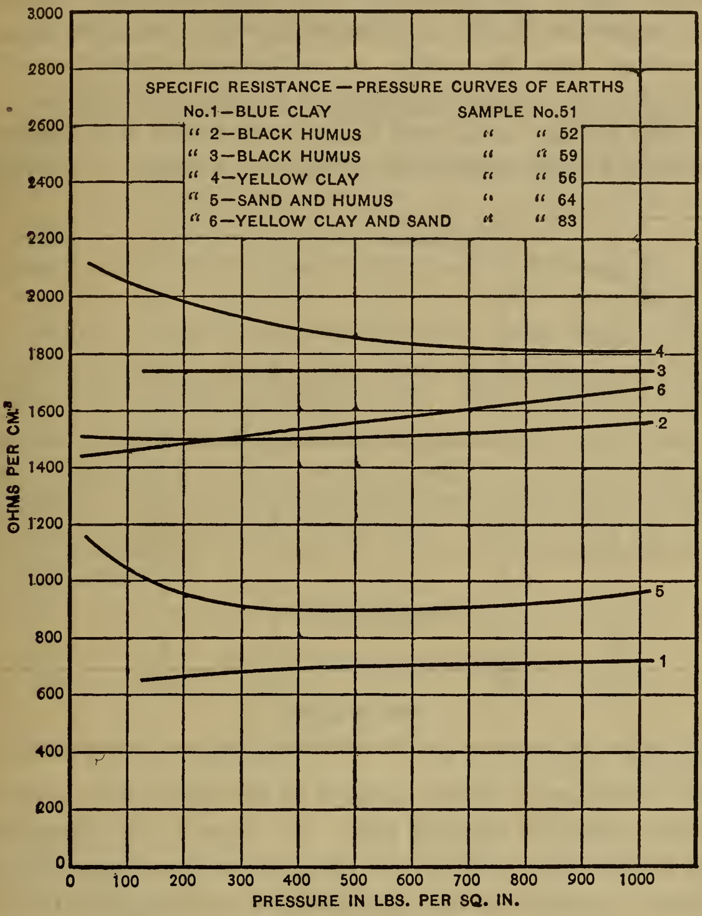

Fig. 9.—*Effect of Mechanical Pressure on Earth Resistance*

4. OTHER FACTORS AFFECTING CURRENT FLOW

There are other factors also which affect the resistance of soils, such as its mechanical properties and chemical constituents, and these may have an important bearing on current flow to and from the buried pipes. The character of the street railway roadbed is also an important factor in determining the extent of leakage of stray current into the earth. A well-drained rock or concrete roadbed may in general be expected to offer much higher resistance to the leakage of current than one in which the construction is such that a large amount of moisture is retained. Polarization and film resistances at the surface of the pipes may also be an important factor in current flow. As soon as an electromotive force is applied to a buried pipe the current flow drops off rapidly with time, especially during the first few minutes, due to the setting up of counter emf's and the formation of film resistances. The extent to which this may occur in some cases is shown in Fig. 10, which shows the effective resistance as a function of time after the application of an emf of about 6 volts between two short lengths of cast-iron pipe buried about 12 feet apart. From this it will be seen that the initial resistance of about 18 ohms has

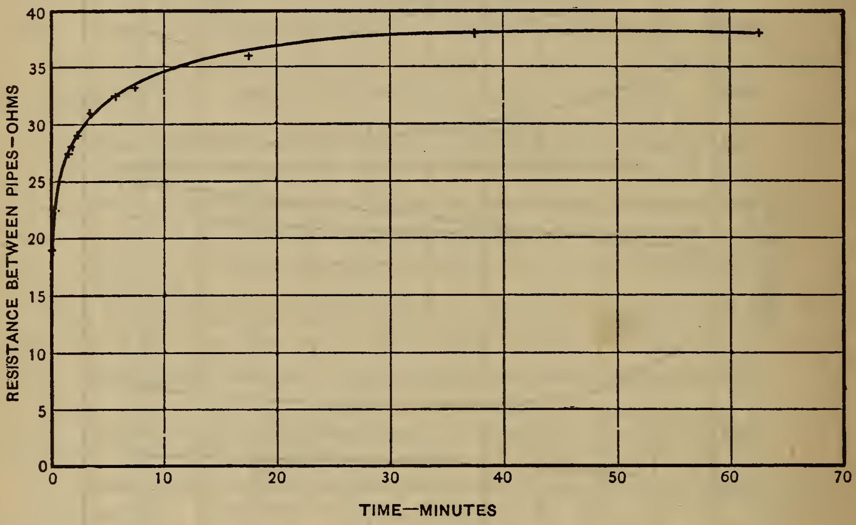

Fig. 10.—*Effect of Polarization and Film Resistance on Resistance Between Buried Pipes*

practically doubled within half an hour after the emf is applied, and after that the resistance remains practically constant. In this case the effect of the polarization and film resistance is practically as great as the total soil resistance between the pipes. These results were obtained when the soil was very wet, and it is probable that in a comparatively dry soil the effect would have been less marked.

5. RESISTANCE OF SOILS FROM DIFFERENT SOURCES

In order to give an idea of the order of magnitude of the resistances that may be expected in practice, together with the range of variation of the same, we give herewith a table of resistances of soils taken from various points in the cities of Philadelphia and St. Louis and other cities. In all of these the specific resistance of the soil is measured with the same moisture content which it had when first taken from the ground, and all were measured at about one temperature. The soils from each city were taken from widely scattered points and represent a great variety of different kinds of soils, as will be evident from the brief description. The moisture content was determined in each case and is given along with the other data. The results are shown in the following table:

TABLE 16

Specific Resistance of Soils

PHILADELPHIA SOILS

No.	Character	Moisture	Specific resistance
		Per cent	Ohms—cm^3
1	Moist gray clay	11.7	651
2	Moist yellow clay	14.8	3850
3	Moist blue clay	16.1	3036
4	Near dry red sand	7.6	2700
5	Moist red clay	17.4	8820
6	Nearly dry mica schist	4.7	156 400
7	Nearly dry gray clay	16.2	5930
8	Nearly dry clay rock and cinders	17.9	595
9	Moist blue clay and gravel	13.1	2830
10	Moist blue clay	15.3	1605
11	Moist yellow clay	17.2	5340
12	Moist yellow clay and sand	13.4	6280

TABLE 16—Continued

Specific Resistance of Soils—Continued

PHILADELPHIA SOILS—Continued

No.	Character	Moisture	Specific resistance
		Per cent	Ohms—cm^3
13	Wet gravel	11.0	24 550
14	Wet humus and clay	9.5	2600
15	Moist clay sand cinders	17.4	2060
16	Damp disintegrated schist	12.9	12 100
17	Wet clay cinders gravel	16.8	5000
18	Moist yellow clay	19.4	4825
19	.....do	17.3	3820
20	Moist red clay	19.3	21 200
21	Moist yellow clay	15.6	25 900
22	Moist red sand and clay	15.7	13 700
23	Moist clay cinders sand	13.7	1494
24	Moist clay and sand	20.0	821
25	.....do	18.7	1774
26	Damp clay and humus	16.7	2490
27	.....do	16.2	2585
28	Near dry disintegrated schist	0.3	610 000
29	Damp yellow clay	16.8	2250
30	Moist yellow clay	18.5	2455
31	Saturated clay and cinders	23.8	4410
32	Moist clay and sand	18.6	6260

PITTSBURGH SOILS

33	Damp sand	13.4	4506
34	Moist yellow clay	16.5	2819
35	Moist clay and humus	20.5	2300
36	Blue clay	26.5	14 025
37	Moist gray clay	26.3	619
38	Damp sand	13.0	1335
39	.....do	10.2	8709
40	Loam and cinders	21.8	1074
41	Near dry sand	12.3	2908

ERIE SOILS

42	Moist clay and gravel	6.0	18 080
43	Clay coal gravel	16.7	1796
44	Wet blue clay	19.3	3779
45	Moist blue clay and sand	11.9	3080
46	Moist gravel	5.7	14 025
47	Wet blue clay and sand	19.6	2462

TABLE 16—Continued

Specific Resistance of Soils—Continued

ST. LOUIS SOILS

No.	Character	Moisture	Specific resistance
		Per cent	Ohms—cm^3
50	Wet clay	20.4	600
51	Blue clay	21.1	700
52	Moist virgin soil	20.8	1500
53	Moist yellow clay	21.5	1250
54	Yellow clay	19.0	1800
55	.....do	....	1600
56	.....do	21.1	1800
57	.....do	22.8	1400
58	Yellow clay	21.3	1400
59	Virgin black soil	21.2	1700
60	Yellow clay	16.0	1800
61	.....do	23.4	990
62	.....do	18.4	700
63	.....do	21.9	950
64	Sand and humus	17.8	925
65	.....do	20.0	900
66	Blue clay	22.0	470
67	Virgin yellow clay	19.1	1450
68	.....do	22.5	484
69	Yellow clay	22.0	700
70	Virgin yellow clay	20.0	1700
71	Virgin soil	22.9	840
72	Yellow clay	23.3	900
73	Blue clay	26.1	400
74	.....do	19.1	600
75	.....do	24.2	830
76	Moist blue clay	23.1	500
77	Near dry yellow clay	16.4	1100
78	Blue clay	17.1	650
79	Yellow and blue clay	26.9	600
80	.....do	19.7	820
81	Blue clay	20.0	750
82	Clay and loam	19.2	1450
83	Sandy clay	19.5	1600
84	Yellow clay	22.6	1200

APOLLO, PA., SOIL

48	....	30.5	1796

ALBUQUERQUE, N. MEX., SOILS

85	....	15.3	43 960
86	....	11.1	59 475
87	....	11.9	41 908

TABLE 16—Continued

Specific Resistance of Soils—Continued

WASHINGTON, D. C., SOILS

No.	Character	Moisture	Specific resistance
		Per cent	Ohms—cm^3
88	Air-dry red clay	4±	2 340 000
89	Near dry	10	14 660
90	Moist loam	20	8729
91	Wet yellow clay and sand	30	41 490
92	Wet humus, clay, and sand	30	24 060

An examination of this table reveals some striking differences in two particulars: In the first place, the specific resistances found in St. Louis show a much greater degree of uniformity than those found in Philadelphia. The extreme range of values of specific resistance for St. Louis earths is between 400 and 1800 ohms per centimeter cube, while for Philadelphia the range is between 595 and 610 000 ohms per centimeter cube. The other chief point of difference is the magnitude of the mean value of resistance, the average value of the specific resistance for all the samples taken in St. Louis being 1053 ohms, while the average for the Philadelphia samples was 28 750 per centimeter cube, the latter being over 27.3 times the former. It should be noted, however, in making this comparison that the high average for Philadelphia is due to a large extent to the abnormally high resistance of two samples containing large quantiites of mica, one of which had a specific resistance of 156 400 ohms and the other 610 000 ohms. If these two are eliminated, the remaining 31 specimens show an average for Philadelphia of 5885 ohms per centimeter cube, which, however, is still over 5.6 times the value for St. Louis. It is quite probable that this difference is such as to prove an important factor in the electrolysis situation in the two places.

IV. CONCLUSIONS

The following are some of the more general conclusions that may be drawn from the experimental data presented in this paper:

1. The current density has a marked effect on efficiency of corrosion of iron in soils, the efficiency of corrosion being, in general, greater the lower the current density. In saturated soils

the corrosion may vary between 20 per cent and about 140 per cent for the range of current densities between 5 milliamperes and 0.05 milliampere per square centimeter.

2. Moisture content in the soil also has a marked effect on efficiency of corrosion, the corrosion efficiency being in general greater with increasing moisture content up to saturation of the soil. Beyond this point increased moisture content has comparatively little effect.

3. Temperature changes within the limits commonly met with in practice have no important effect on corrosion efficiency.

4. The depth of burial of pipes has no direct effect on corrosion efficiency provided other conditions remain constant. In practice, however, the moisture content, current carried by the pipes, and various other factors which affect corrosion efficiency will vary with depth, so that indirectly differences due to depth may be noted.

5. The amount of oxygen present has no appreciable effect on the efficiency of corrosion in the case of iron immersed in liquid electrolyte.

6. Corrosion efficiency of iron embedded in earth is always greater in open vessels than in sealed vessels.

7. The amount of oxygen present has a marked effect on the end products of corrosion. If the corrosion is rapid and the supply of oxygen small, there will be a preponderance of magnetic oxid, while if the rate of corrosion is low and the supply of oxygen abundant the ferric oxid will predominate. Owing to the fact that the supply of oxygen around pipes buried in earth is always more or less limited, the character of the oxids formed gives some indication as to the rate of corrosion, and thus indirectly the cause of the corrosion, if local conditions are properly considered.

8. There is no material difference in the efficiency of corrosion shown by the various kinds of iron commonly used in the manufacture of underground pipes.

9. The fact that a given chemical tends strongly to inhibit either self-corrosion or electrolytic corrosion in liquids is no indication that it will materially retard electrolysis of iron embedded in soils.

10. Pitting of iron embedded in soils is affected not only by a nonhomogeneous condition of the iron or soil, but also by the chemicals contained in the soil.

11. The efficiency of corrosion was found not to be a function of the voltage except in so far as the current density may be affected. Voltages as low as 0.1 and 0.6 volts showed practically the same efficiency of corrosion as 5 to 10 volts or higher.

12. Corrosion tests on a large number of different kinds of soil from widely different sources with average moisture content and moderate current density indicate that corrosion efficiencies between 50 and 110 per cent may usually be expected under most practical conditions.

13. The resistance of soils varies throughout a very wide range with variations in moisture content, the resistance of the comparatively dry soil being of the order of several hundred times the resistance of the same soil at about saturation. Above saturation, increase in moisture content has but little effect on the resistance of the soil.

14. Because of the great variations in resistance of earth with moisture content, voltage surveys should not be made at times when the earth is extremely dry.

15. The resistance of the soil varies greatly with temperature within the ordinary range encountered in practice. In the case of the soil tested the resistance at 18° below zero centigrade was over two hundred times as great as at 18° above zero centigrade. Even at about freezing temperature the resistance will be several times that at summer temperatures. This not only has an important bearing on the magnitude of the electrolysis trouble that may occur at different seasons, but it also indicates that where practicable voltage surveys should not be made when extremely low temperatures prevail.

16. The experimental results given in this paper have an important bearing on the subject of electrolysis mitigation through the limitation of voltage drop in the negative return. For some years the chief means of preventing trouble from electrolysis in certain foreign countries has been the limitation of the permissible voltage drop between any two points on the return circuit. In some places the limit has been placed on the maximum voltage during

peak load, whereas in other cases the average voltage for 24 hours has been the determining factor. It will be evident that if the total amount of damage which results is proportional to the average current, then the limitation of the average voltage would be more logical than the limitation of the peak-load voltage, since in the former case the cost of meeting the voltage limitation in any given case would be proportionate to the danger involved irrespective of the station load factor; whereas if the voltage at peak load is the determining factor the cost of complying with the requirements depend not only on the danger involved but on the load factor of the system, and the poorer the load factor the greater its cost will be. It appears from the data presented in this paper that the rate of damage does not increase as fast as the voltage increases, because of the tendency toward lower corrosion efficiencies at higher current densities. This indicates that, with a given average all-day current the actual amount of electrolysis that would occur would be less with a bad load factor than with a good load factor, and hence points to the undesirability of penalizing a high peak of short duration. It would appear more logical, therefore, in so far as the damage itself is concerned, to make the average all-day voltage the basis of the limitation rather than the voltage at time of peak load.

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